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Development of A Cost-Benefit Model for Shipping in the Arctic

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ABSTRACT OF THE
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This thesis project outlines the development of a Cost-Benefit Model (CBM) for shipping in the Arctic, considering the requirements outlined in the newly adopted Polar Code. The model is constructed to provide a live feasibility decision making tool for comparing vessels transit times, expenses, operational limitations and need for icebreaker escort; on either the Northwest Passage, Northern Sea Route, Suez Canal Route, or Panama Canal Route. The model inputs ship parameters, ice conditions, and economic factors including: additional insurance premiums, canal tolls & transit tariffs, port fees, competent crew costs, bunker price, and unexpected maintenance costs due to ice damage. The model was developed using relevant information gathered from literature on both economic feasibility studies and ship-ice interactions, as well as from interviews with ship owners and operators with invested interests in Arctic shipping.

The CBM is used to run a research simulation for two cases studies representing the highest and lowest cost differentials between the southern and northern routes. From these two case studies, it was found that fuel costs are the largest contributor to total voyage expense and that this cost is directly influenced by the ship speed in ice calculation routine. A Polar Class 4 and Finnish-Swedish 1A ice class ships were compared within the research simulation. The results show that either ship on the northern routes is a feasible option as the interpretation of the CBM results must be considered from both a time-saved and revenue earned perspectives. The CBM results are dependent on the ice data input, the accuracy of the voyage, operational and capital inputs as well as the market conditions according to which the results are to be analyzed and compared under.

Keywords: Polar Code, POLARIS, Arctic Shipping, NSR, NWP

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Grandinetti S. Teekkari

Contents

Abbreviations

Abbreviation	Definition
$CAPEX$	Capital Expenses
CBM	Cost Benefit Model
CCG	Canadian Coast Guard
C_n	Ice Type Concentration within a set ice regime
$DNVGL$	Det Norkse Veritas, Germanischer Lloyd
DW	Dead weight
DWT	Dead weight tonnage
$FS1A$	IACS Finnish-Swedish 1A Ice Class Ship
$FSIC$	Finnish-Swedish Ice Class
$FSICR$	Finnish Swedish Ice Class Rules
$IACS$	International Association of Classification Societies
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
LNG	Liquid Natural Gas
$MEPC$	Marine Environment Protection Committee
$MARPOL$	International Convention for the Prevention of Pollution by Ships
MDO	Marine Diesel Oil
MSC	Maritime Safety Committee
NDF	Naval Distillate Fuel
nm	Nautical Miles
NSR	Northern Sea Route
$NSRA$	Northern Sea Route Administration
NWP	Northwest Passage
$OPEX$	Operational Expenses
$PC4$	IACS Polar Class 4 Ice Class Ship
PCR	Panama Canal Route
$PCNT$	Panama Canal Net Tonnage
$P\&I$	Protection and Indemnity Insurance
$PWOM$	Polar Water Operational Manual
$POLARIS$	Polar Operational Limit Assessment Risk Index System
RFR	Recovery Freight Rate
RIO	Risk Index Outcome
RIV	Risk Index Value
$RORO$	Roll On - Roll Off
SCR	Suez Canal Route
$SCNT$	Suez Canal Net Tonnage
$SOLAS$	Safety of Life at Sea
t	Metric Ton
USD	United States of America Dollars
$VOYEX$	Voyage Expenses
WMO	World Meteorological Organization

Chapter 1

Introduction

As the polar ice caps melt the availability of using the Arctic seaways, the Northwest Passage through the Canadian Archipelago or the Northern Sea Route across the top of Russia, as feasible shipping lanes to decrease the distance of shipping between Europe, Asia and North America has increased. However, passage across the Arctic presents many unique challenges and risks impacting the environment, economy of the Arctic states, safety to crew and passengers, available infrastructure and economic feasibility [PAME Arctic Council, 2009].

Polar waters present several challenges to mariners traveling through them. Ships are travelling in remote areas, often far away from other vessels or the nearest safe haven, with poor quality hydrography that limits the communication and navigation equipment in remote regions [Kendrick, 2016]. Crews will likely encounter sea ice of various strength and thickness, topside ice from sea spray, low temperatures, long dark nights or long bright days, quick changing and severe weather, and possible lack of experience amongst themselves. All of these factors increase the risk of travelling through polar waters. The International Maritime Organization (IMO) mandated Polar Code came into force January 1, 2017 with the intention of "increas[ing] the safety of ships' operation and mitigate the impact on the people and environment in the remote, vulnerable and potentially harsh polar waters" [IMO, 2016b, Shipping in Polar Waters].

From 1992 IMO had an outside working group start to develop the first proposal for the Polar Code. In 2002 voluntary guidelines for Arctic waters only was proposed as Maritime Safety Committee (MSC) Circular 1056/ Marine Environment Protection Committee (MEPC) Circular 399, "Guidelines for Ships Operating in Arctic Ice Covered Waters" [Kendrick, 2016]. In 2009 this was updated to "Guidelines for Ships Operating in Polar Waters" under IMO Resolution A.1024(26). This was to reflect the need of guidelines for the Antarctic region as well. Five years later the Polar Code was adopted during the 94th session of IMO's MSC and the 68th session of the MEPC seven months later. On January 1st, 2017 the Polar Code entered into force as mandatory amendments to both the Safety of Life at Sea Convention (SOLAS) and the International Convention for the Prevention of Pollution by Ships

(MARPOL) [IMO, 2016b].

The amendments to both SOLAS and MARPOL, represent Parts I and II of the Polar Code respectively. Each of these parts is also divided into two sections Part A the mandatory regulations and Part B which consists of recommended guidelines for safety that help to practically explain adherence while still leaving room for alternative practices. The code applies to all vessels over 500 gross tonnage. The Polar Code addresses three categories of ship safety: equipment, design & construction and operations & manning, which are covered in thirteen chapters in Part I-A. As well as five categories for environmental protection: oil, invasive species, sewage, garbage and chemical, covered in Part II-A. [IMO, 2016a].

1.1 Motivation

The Polar Code has been developed over the last 25 years, and has existed as guidelines for many years. With it's entrance into force this year, the guidelines have now become goal-based mandatory amendments to SOLAS and MARPOL and the impacts of this are yet to be realized. This provides a new perspective for economic feasibility studies to focus on: the implications of the Polar Code on the economics of Arctic shipping. For some ship owners and operators the Polar Code will have very little impact on their operations as they have already been adhering to the IMO's Guidelines for Ships Operating in Arctic Ice Covered Waters, for years. However, for newer players in the Arctic oceans the Polar Code may introduce some challenges that are now mandatory to overcome should they wish to ship through the Arctic. The thirteen categories presented in Part I-A of the code present questions around required changes to crew training, navigational equipment, stricter route planning, upgraded safety equipment and polar certification. The construction limitations outlined in Part-IA, are for the most part consistent with the rules already outlined in the International Association of Classifications Societies (IACS) class notations for Finnish-Swedish Ice Class (FSIC) and polar class ships. However, the amendments to MARPOL could have a larger effect on ship structural construction, particularly around the required size of holding tanks for garbage and sewage and ballast water treatment [Tanker Shipping & Trade, 2017].

Since the early 20th century the Arctic seaways have been getting more and more accessible as technology increases and the melting polar caps leave more ice free waters accessible. This has drawn researchers to look at detailed cost benefit analysis', performed from a shipping perspective, on the feasibility of using the Arctic seaways as a viable shipping route to save both time and money when compared to the southern routes. However, many of these studies do not go into detail on the effects of ice conditions on the speed and fuel consumption of the ship. On the other hand, the research for more accurate ship transit simulations in ice often ignore detailed cost analysis considering insurance, tariffs, fuel costs, or political influence. There is not a lack of literature addressing the potential impact the in-force Polar Code may have on shipping in the Arctic, however there are few detailed studies on the topic.

One of the requirements of the Polar Code, that may have a significant effect on how cost-benefit analysis and ship-ice simulations are run, is the requirement to establish a risk assessment method applied to operational limits in ice covered waters. Part-IB of the Polar code proposes a system to handle this requirement, called the Polar Operational Limit Assessment Risk Indexing System or POLARIS. POLARIS assesses risk based on the ice regime, the ice class of the ship and if the ship is escorted by an icebreaker. This operational limitation assessment impacts a ship-ice simulation by adding an additional component to consider when calculating a ships allowed speed through a certain ice regime. This also effects any cost-benefit analysis' that have assumed a constant speed through the Arctic seaways for their calculation of voyage time and associated fuel costs, which are arguably some of the biggest contributing factors of a cost-benefit analysis [Lasserre, 2015].

Another issue that arises for cost-benefit analysis' is the instability, unpredictability or lack of information for academics on several factors that indirectly effect the cost comparison between the northern and southern route. These can loosely be labelled political factors and they include accurate insurance premiums, ability to negotiate canal fees and political stability that may effect the levels of piracy in a region, the availability of icebreaker or search and rescue support.

1.2 Cost-Benefit Model

This thesis project involves the construction of a Cost-Benefit Model (CBM) that considers in detail the requirements outlined in the Polar Code. The model takes inputs such as ship parameters, ice conditions, & political scenarios and outputs a breakdown of voyage and ship management costs associated with Arctic transits through either the Northwest Passage (NWP) or the Northern Sea Route (NSR) in comparison to transits using the Panama Canal Route (PCR) or Suez Canal Route (SCR). The completed model is able to use real-time ice data to provide a live economic decision making tool on the cost benefits of utilizing the Arctic seaways.

The model uses relevant literature on the economic feasibility of shipping in the Arctic, data collected from interviews and surveys with companies invested in Arctic shipping, ship resistance & speed in ice theory, as well as the Polar Code and POLARIS texts and supporting documentation to capture voyage, operational & capital costs associated with Arctic shipping.

The simulation scenario used in this thesis project is comprised of two routes. The first utilizes the Suez Canal or the Northern Sea Route between Kokkola, Finland and Shanghai, China. The second utilizes either the Panama Canal or the Northwest Passage between Kokkola, Finland and Vancouver, Canada. The ice data used is monthly averages of ice type and concentration for both the NSR and NWP.

For this thesis project the completed model is used to compare the benefits of a higher ice class ship versus a lower ice class for shipping bulk cargo through the Arctic. Two ships, one a Polar Class 4 (PC4) ice class and the other a Finnish-Swedish 1A (FS1A) ice class, that have both previously traversed an Arctic seaway, are compared in the simulation. The results of this comparison, input and model bias and the impacts of Polar Code requirements on the simulation are also discussed.

1.3 Model Limitations

Since this thesis project explores the development of a Cost-Benefit Model, there are inherently many assumptions made when presenting results from the model. This is due to the fact that the limitations of the model are directly linked to the quality and accuracy of the model inputs. Throughout this report the assumptions made, at each step of the model construction, are stated, explained and justified.

The main limitations of the this model are in the heavy reliance on accurate ice data and real economic figures. The higher the resolution of the ice data (ice parameters measured for smaller geographical areas), the more accurate the ship speed calculations. This thesis project uses monthly averaged ice data covering large geographical areas. To increase the accuracy of a transit simulation, the number of legs over which specific current ice data is given should be increased.
True economic figures for insurance rates, canal tolls, operational costs, and capital expenses are hard to gather and often vary widely within academic literature. Several companies were interviewed as part of the thesis project in hopes of gathering more accurate figures, however even these values are only valid for a specific ship at a specific time. However, the model has been developed to be flexible and allow an end user to input their own economic figures that reflect their scenarios of interest.

Chapter 2

Background & Supporting Theory

This section outlines all the background theory and information that is compiled for use in the construction of the Cost-Benefit Model. This includes results from previous cost-benefit studies, the break down and discussion of operational costs in eight categories, the calculation routines for ship resistance in ice and open water and finally a summary of how to use POLARIS to dictate operational limitations.

2.1 Previous Cost-Benefit Studies

There are three groups of literature that are important to consider when analyzing the feasibility of the Arctic seaways. Each group adds a component to help construct a larger understanding of the complexities and challenges of shipping through the Arctic. The first is focused on economic feasibility. These studies consider the impacts of insurance, load factor, tariffs and other economic factors. These studies often use a simplified model for predicting ship speed in ice along the Arctic routes, usually using an average speed for the entire transit. The second group is ship transit simulations in ice. These studies, while sometimes including basic economic factors usually taken as constants with little detail on the selection or variability of the value used, focus primarily on factors related to simulating a ships speed through ice. Calculation methods to determine ship resistance in ice are central to these models. The last group is literature on the Polar Code or POLARIS route planning. As the adoption of the Polar Code is very recent, there are few full feasibility studies that include route planning or other Polar Code related factors that now have mandatory compliance.

2.1.1 Economic Feasibility Studies

These studies focus mainly on the economic factors that effect economic feasibility of Arctic shipping, often emphasizing or uncovering the wide range of predictions or lack of existing data.

In Erikstad and Ehlers's [2012] report constructed a decision-support model for liner transport through the NSR. They include the length of the sailing season due to ice covered waters, the initial cost of the ship, the operational and maintenance costs, voyage costs including fuel and crew costs, and finally lost opportunity costs due to decreased cargo carrying capacity for ice strengthened ships; as factors to be considered when analyzing an appropriate ice class vessel for transit in the NSR. They concluded, that based on current trends the most appropriate ice class vessel is a FS1A, as the added expense of a FS1A Super class is too significant.

In 2016, Lasserre and Pelletier conducted a second survey of 189 companies in North America, Asia and Europe about their thoughts on the future of the Arctic shipping market (Lasserre conducted an initial study in 2011). They asked about the commercial potential; important monitoring and navigation systems; perceived costs, challenges and risks; as well as the companies plans for expansion into the Arctic market. The study revealed that shipping companies perceive ice-class ship construction, insurance costs and crew training to be the three largest cost barriers to shipping in the Arctic. While the harsh environment and seasonality are the most significant operational challenges. Icebreaker escort and search & rescue accessibility were identified as the most important navigation services along the Arctic routes.

In his 2015 simulation of Arctic shipping Lasserre evaluated 23 previous models from 1991 to 2012. He concluded that there are several crucial factors that vary widely from model to model and can have large implications on the outcome of the simulations. These include: insurance premiums, crew cost structure, tariffs for admittance & icebreaker assistance, increased capital cost for ice-class constructed ships, accurate ship speed estimates in ice and fuel type and consumption rate. He investigated the use of a PC4 liner vessel for shipping year round on the NWP and found that the additional fuel consumption of the ship due to ice breaking was too expensive to make winter shipping economically feasible. His study did not look at a PC4 ship on the NSR, but he did find that a FS1A ship on that route was not a feasible option for liner trade in the winter either. Lasserre also discussed the importance of a strong load factor in making the Arctic routes feasible.

2.1.2 Ship-Ice Transit Simulations

This group of literature doesn't always include an economic component, instead they describe methods for generating & analyzing ice data and calculating ship resistance and speed in different types of ice. Many of these ship-ice transit simulation studies are also concerned with ice-going route optimization.

In Kotovirta et al.'s [2009] paper a prototype system that integrates satellite ice data, ship-ice resistance calculations and optimization routines for ships travelling in the Baltic Sea. While, this paper is not an economic feasibility study, the ice modelling and ship speed in ice calculations are important in determining the speed of transit for an ice going vessel.

Riska and Valkonen [2014] developed a probabilistic model that can be used to assess the economic feasibility of ship designs. Their paper outlines the importance of ridges in realistically estimating transit time, especially if the ship gets stuck in an ice ridge and requires icebreaker assistance. They argue that a ships speed through ice requires different methods and inputs for different ice types, like ridges. They also stress the importance of having good ice data in order to provide a good ship speed estimate.

In their report La Prairie et al. [1995] outline the construction of a computer model that simulates a vessel transiting through ice covered waters. They include calculation routines for six different ice conditions; open water, channel ice, level ice, ridged ice, compressive ice and pack ice. While originally designed for the Baltic Sea, the input ice parameters could be altered to reflect ice from different regions.

Mulherin et al. [1996] developed a numerical model for estimating transit times across the NSR for various ship types during the summer months. This model uses a Monte Carlo simulation to generate empirical look-up tables for the speed of each leg of the transit. The speed simulation is based on historically data of wind, fog, snowstorms, icing, waves, currents, ice concentration, ice thickness, and ice pressure. Ship operating & ownership costs, icebreaker escort fees, and other passage fees are the economic factors included in their study. This model has the most flexibility in the meteorological variables used to determine speed of a vessel, however the ship-ice interactions are poorly modeled compared to other studies.

2.1.3 Polar Code Impacts

Kendrick's [2016] paper on the implications of the Polar Code addresses six points that he foresees directly impacting current practices within Arctic shipping. These areas are: certifications & approvals, operations, ship construction, equipment, crewing, and environmental protection. One of the largest challenges he sees is with the goal based style the Polar Code is written in, this allows for various interpretations and will require continued cooperation between stakeholders in the marine industry to ensure consistent enforcement and implementation. Kendrick also discusses the difficulty with the Polar Code's proposed paperwork, with each ship requiring a Polar Certificate to be obtained. This certificate will also include a Polar Water Operation Manual (PWOM) that will include a wide range of paperwork pertaining to operation in polar waters.

A study by Stoddard et al. [2016] looks at the advantages of route planning and how POLARIS can be used to allow ship operators or the coast guard to evaluate the kinematic motions of a ship in ice compared to the operational limits POLARIS sets. A ship owner can evaluate the feasibility of an Arctic transit given the current ice conditions, while the coast guard can use this information to asses potential risk areas to ships or to identify whether erratic ship motions are due to safe maneuvers based on current ice conditions or due to a ship in distress.

Kujala et al.'s paper presents their comparison between POLARIS risk index value (RIV) results and full scale ice induced loads. They concluded that POLARIS gives reasonable feedback and operational limitations for risks that are consistent with encountered ice conditions for each ice class. They also discussed the best ice class of ship to be used in polar waters. For Antarctic operation they determined a PC3 vessel was best, and a PC6 vessel was best for the NSR. These recommendations were based off of the POLARIS RIV's of these ship being in the operation permitted category of the POLARIS operational limitations. The RIV's were calculated from the observed ice regimes and ice thicknesses.

2.2 Voyage, Operational & Capital Costs

When considering the feasibility of a ship transiting the Arctic seaways there are many factors to take into consideration that have the potential to impact a simulation. The economic factors can be divided into three main sections: voyage, operational and capital costs. As part of this project several ship owner and operators were interviewed on their experience with Arctic shipping both in the NWP and NSR. The companies comments are explored alongside literary reviews in the following sections.

2.2.1 Voyage Costs

Fuel Type & Consumption

Fuel costs are arguably the largest variable in a cost analysis of Arctic shipping [Lasserre, 2015]. The fuel costs for a voyage are dependant on the fuel consumed during the voyage and the price for the fuel used.

Fuel consumption is proportionate to engine power, engine efficiency and time of transit. These variables can be accounted for by assuming that the fuel used on a voyage is only the fuel required to compensate for the ship's encountered resistance. This is done by letting the velocity of transit (time) vary, and assuming a constant engine efficiency.

The most common grades of marine fuel are marine diesel oil (MDO) or intermediate fuel oil (IFO). These grades are low cost and perform well in most ocean conditions, however they may not be the best suited for cold-water operations. The Canadian Coast Guard (CCG) uses a naval distillate fuel (NDF) for all of it's Arctic operations [Lasserre, 2015], as it has a lower freezing point than MDO or IFO. NDF is more expensive compared to the widely available MDO and IFO, however in the winter ships operating in the Arctic may have to consider using a distillate fuel instead of MDO or IFO. One company who operates their ships year round in Canada's Arctic, uses only IFO for these voyages, however it should be noted that these ships were designed for polar operations and were constructed so that IFO fuel could be used year round with no concerns.

Insurance

While insurance is often included under operational costs, in this model insurance refers solely to additional premiums above and beyond Protection and Indemnity (P&I) insurance that would be required on all routes, under the International Navigation Limits.
Most insurance companies explicitly rely on documents from IACS and IMO concerning navigation and operations in ice covered waters, including the Polar Code, to assist them in determining reasonable requirements of coverage for ships wishing to transit the Arctic seaways [Sarrabezoles et al., 2014]. Even though the insurance companies rely on standardized systems to aid in their premium calculations, there still seems to be a wide range of predictions from various researchers as to how expensive insurance premiums will be for ships wishing to transit through the Arctic. Insurance companies consider the Arctic experience of the crew, availability of icebreakers and distance to port in case of emergency, as well as ice class and weather conditions to set their premiums for Arctic going ships. This implies that insurance premiums will likely be higher for the NWP compared to the NSR as there are less intermediate ports and fewer icebreakers to offer assistance along the NWP [Lasserre, 2015].

Companies discussed their experience with insurance for ice covered water as a relatively straightforward process. Because of these particular shipping and insurance companies previous experience and knowledge with ice going vessels the insurance process was likely much smoother than it would have been for a new player in Arctic shipping. The insurance premium quoted for the very first NSR transit was high for one company, however after negotiations and with proof of experience on subsequent voyages the insurance premium for additional risk due to ice was reduced to around a quarter of the original quote. One factor mentioned by all companies was their previous experience with shipping in the Baltic Sea in the winter and the insurance companies confidence in the shipping companies experience and investment in safety when shipping in ice covered waters. They mentioned that a company new to shipping in the Arctic or ice covered waters would likely be given higher premiums until they had proven their competency. Additional insurance premiums for both the NSR and SCR were reported by companies in their interviews. They noted that one of the reasons the NSR was a profitable choice in 2011-2013 was because of the high additional premiums for armed guards in the SCR, due to piracy concerns along the Somalian coast at that time.

Canal Tolls & Transit Tariffs

Of the four routes explored in this project, only the NWP currently does not charge a toll or tariff, however there is a fee for icebreaker assistance. The calculation and dependant variables for the tariff charge differs for the SCR, NSR and PCR. The tariffs imposed for each canal/route differ substantially from each other and are an important consideration when calculating voyage costs.

Suez Canal Toll

The Suez Canal Authority (SCA) bases their Gross Ton Dues off the Suez Canal Net Tonnage (SCNT) and type of vessel. The SCNT is calculated as: " the exact measurement of all spaces (without any exception), below the upper deck, as well as of all permanently covered and closed -in spaces on that deck" [Suez Canal Authority, 2008b]. Each ship wishing to pass through the SCR needs to obtain a SCNT Certificate from authorities. Imposed tugs, pilotage and slow speed allowances are additional fees for ships that require these services [Suez Canal Authority, 2008a].

Panama Canal Toll

The PCR like the SCR uses the type of vessel as a basis for their toll calculation. The vessel type, cargo carrying capacity (measured in maximum TEU capacity for container ships, deadweight for dry bulk carriers and Panama Canal Net Tonnage (PCNT) for chemical, RORO Vehicle, passenger and general cargo vessels. LNG carriers are charges by cubic meter of cargo) and overal length and maximum breadth [Panama Canal Authority, 2017].

NSR Admittance and Icebreaker Tariffs

The tariff charged for admittance to the NSR depends on how many stages the ship will transit, the ships gross tonnage and the ice class of the ship. The NSR information office defines seven stages of the NSR. (Kara Sea-SW, Kara Sea-NE, Laptev Sea-SW, Laptev Sea-NE, East Siberian Sea-SW, East Siberian Sea-NE, and Chukchi Sea). Tariffs are more expensive for longer journeys, larger GT's and lower ice classes. The Northern Sea Route Administration (NSRA), dictate what levels of ice classes are allowed to transit through the NSR depending on the ice conditions found there at the time of transit, as well as which ships require icebreaker assistance and in what conditions. Most ships transiting the NSR that are not icebreakers themselves, require a Russian icebreaker escort to comply with NSRA rules [Northern Sea Route Information Office, 2013]. While the NSR information office provides a calculation for the maximum tariff, the actual final tariff charged is often negotiable with the NSRA .

When asked about their experience dealing with the NSRA, companies stated that they were very professional and easy to work with. The negotiation of icebreaker assistance and tariff was based more on pragmatics than regulations, with the cost for the transit closely mirroring the current cost of the SCA toll. The ice pilot was an additional cost of around $1,000 USD per day plus travel expense. Table 2.1 show the average additional expenses for the NSR.

Table 2.1: Average Additional Expenses for NSR Transit [Compiled from Company Interviews]

Additional Expenses	**Cost in USD**
NSR Tariff & Icebreaker Escort	250 000
Ice Pilot (per day + travel)	20 000
Certifications, Charts, Other	10 000
Additional Risk Due to Ice	50 000
Unexpected Reapir Budget	25 000
Total NSR Additional Expense	*355 000*

NWP Icebreaker Fee

The CCG has 15 icebreakers most of which operate in the Saint Lawrence river and along the East Coast [Canadian Coast Guard, 2016]. The CCG charges a flat rate for icebreaker services with reductions offered for higher ice classed ships. The fee is charged every time icebreaker assistance is required, up to a maximum of 3 calls within 30 subsequent days. The CCG maintains that in average weather conditions icebreaker assistance is at most 10 hours away in the Canadian Arctic [Minister of Fisheries and Oceans, 2013].

Ports of Call

The three ports considered in this project are Kokkola in Finland, Shanghai in China and Vancouver in Canada. Port costs, while contributing to the calculation of overall cost for a voyage, will be considered identical irrespective of which route was taken and what ice class the ship carries, with the exception of calculating Finnish fairway dues at Kokkola.

Finnish Fairway Dues

Finland has adopted fairway dues for merchant vessels that call at Finnish ports. The fairway dues are collected to finance the icebreaker service offered by the Finnish Transport Agency that keeps Finnish ports open year round, regardless of ice. The fairway dues are more expensive for lower ice class ships and less expensive for ships carrying a FSIC 1ASuper ice class or higher. The reasoning is that ships with higher ice classes will be more self-sufficient in Finnish waters and thus less likely to need emergency icebreaker assistance. Finnish fairway dues are based on the net tonnage shown on a ships tonnage certificate as a per ton unit rate which is determined by the ice class of the vessel [Finnish Transport Safety Agency, 2014].

2.2.2 Operational Costs

Maintenance

Damage caused by ice is a likely event for ships travelling in ice covered waters. Scratching of paint from ice along the hull is inevitable, and the risk of unexpected damage is larger than in ice free waters. A study done in 2005 analyzed the risk associated with ice damage on ships traveling in the Baltic Sea [Jalonen et al., 2005]. They found that the three most likely damages to incur are hull ice damage, collisions and propeller damage. Hull ice damage is often due to ice scratching paint, with a smaller percentage of incidents involving frame damage or ruptures. Collisions most commonly occur in convoys when ships are following too closely and are unable to stop fast enough. Propeller damage is caused by hard ice chunks hitting the propeller, or getting lodged between the hull and propeller blade. All of these damages require maintenance that is above and beyond the expected maintenance cost of ship travelling in ice free waters.

It was found in the company interviews an average of $25,000 USD per NSR transit was budgeted to cover ice damage repair costs. Ice damage was incurred on about 30% of the NSR transits, with the majority of the incidents effecting the fore-shoulder and the other third effecting the bow. The greatest risk to ships in the NSR are growlers, large mostly submerged ice floes that sometimes drift in between the ship and the escorting icebreaker. When the ship strikes a growler there is often damage done to the hull, although since these are usually double hull tankers the damage is only superficial and not structurally compromising.
Ships travelling in the NWP incur ice damage very similarly to the NSR. Ships don't travel in convoys as they do in the NSR which makes ship-to-ship collisions less likely to occur, however since icebreakers are utilized less, the ice damage caused from ice breaking itself is more likely to occur.

Competent Crew

The Polar Code outlines the ice training requirements, for the master, chief mate and officers in charge of a navigational watch, for all vessels sailing in waters with any ice present. If the ice concentration is less than 10% basic ice training is required for the officers of tankers and passenger ships. However if the ice concentration is over 10% then all ships must have advanced training for the master and chief mate and basic training for any officers in charge of a navigational watch [see IMO, 2016a, Chapter 12 of Part I-A]. Ice training with the explicit intent of fulfilling the Polar Code requirements is not a widely available course, however with the Polar Code coming into effect only recently this is likely to change very quickly.

The crew onboard the ships that transited the NSR between 2011-2013 often did not have advanced ice training. One company mentioned that their crew had had ice training on an ice simulator in Manila. It was unclear on the level of training this crew had received compared to the level of training required by the Polar Code, although they suspected that additional training, particularly for the officers, would be required to obtain a polar certificate under the Polar Code.

Another company mentioned that, since the Polar Code is goal-based, there would likely be a period of time between the code entering into force and the code being enforced to the letter, where the previous ice experience of the crew would count towards competency in ice. Ultimately, they stated that it is in the shippers best interest to have an ice navigator(s) onboard as, tools such as ice charts and voyage planning systems, like POLARIS, don't completely depict the reality of individual ice regimes.

2.2.3 Capital Costs

Initial Investment

The operational costs classified under initial investment include the additional cost required to build a higher ice class ship as well as any modifications or upgrades that would be required by current ships in order to meet the Polar Code requirements and obtain their Polar Certificate.

Ice Class Comparison

Ice strengthened ships are a larger initial investment, due to the increased hull weight and required power. An accurate assessment of the increase in capital cost is hard to acquire. Lasserre [2015] compiled the estimates from 17 other studies and they estimate a 20% increase in capital cost for a PC7 ship and a 30-40% increase for PC4 or higher ice classes.

When one company was asked if they would ever consider building a higher ice class tanker, compared to their current FS1A ships, their immediate response was yes that would be such an interesting project! However, they had to admit that there would need to be significant changes in the market to justify the cost to their stakeholders for the NSR route. They cited the following changes required:

- An increase in bunker fuel prices would make the fuel savings in a shorter transit time more relevant to cost savings.
- Since 2013 the Russian political situation has dictated that Russian icebreakers are no longer guaranteed along the NSR for assistance as their priority is now the Russian Navy. Were the situation to stabilize and icebreaker assistance be more dependable this would decrease safety concerns.
- When Russia re-directed trains carrying oil to the St. Petersburg terminal instead of the White Sea Terminal they removed the market for LR1 tankers required to carry oil from the White Sea to Asian markets. A new market opening up shipping oil products from northern Norway or Russia to the Asian markets or vice-versa would be required to be profitable.

The NWP has different concerns as ice conditions are more severe and icebreaker assistance is not as readily available as on the NSR. Companies stated that this has led them to very serious consideration of higher ice classes in order to maintain a year round shipping operation in the Canadian Arctic. They pointed out that even with ice breaker assistance (which is very rarely used) the ice conditions in the NWP in the winter are too difficult to pass through without a polar class 3 or 4 (or equivalent) ship.

Polar Code Compliance

The Polar Code introduces several new requirements on ships to be used in the Arctic, especially in Part II as adopted under MARPOL. The limitations set by the Polar Code on discharging onboard waste, may require vessels to be built with larger holding tanks in order to carry the waste until the vessel leaves the Arctic regions, or is far enough away from an ice shelf to safely discharge [Tanker Shipping & Trade, 2017]. This becomes particularly important in the winter where ice conditions of less than 1/10 ice concentration are unlikely. This may present a problem for already constructed ships as their waste storage tanks may not be large enough to comply with the regulations.

Already constructed ships may also have to retrofit their existing ships to account for the safety requirements of the Polar Code like winter clothing available for all persons onboard, covered life rafts & lifeboats, availability of immersion suits, deicing tools & preventative equipment [Kendrick, 2016].

Ghosh and Rubly [2017] discusses five other concerns with Arctic shipping that, while not all are included explicitly in the Polar Code, are of importance to consider when designing a ship for commercial shipping in the Arctic regions.

- Oil pollution, is discussed in the Polar Code with requirements set on the distance between oil fuel tanks and the outer shell. Oil tankers also have special structural requirements. Operationally all ships are prohibited from discharging into the sea any oil or oily mixtures [IMO, 2016a]. The biggest issue with carrying heavy fuel oil through the Arctic is the catastrophic effects for both wildlife and environment. Especially considering "the region's remoteness, lack of infrastructure and extreme weather conditions" [Ghosh and Rubly, 2017].

- Invasive aquatic species could be introduced to the Arctic's delicate marine environment through ballast tank discharge or bio-fouling. This issue is not directly addressed in the Polar Code, although there are many calling for this issue to be addressed in written legislation.

- Marine mammal displacement is caused by marine noise. Icebreakers are very noisy ships, due to their machinery noise and of icebreaking itself. Properly designed propulsion systems and machinery can have a large impact on the noise levels of a ship. This issue is also not addressed in the Polar Code, but an IMO sub-committee has put together information concerning methods to reduce ship noise that is applicable to all ships.

- Carbon emissions are not addressed in the Polar Code, despite research showing their contribution to Arctic climate warming. A proposed solution to this is to extend the Emissions Control Areas (ECA) to include the NSR and NWP. It should be noted that any ship transiting from a southern latitude within the current ECA into the Arctic would already be required to comply to MARPOL regulations, however any ships operating solely in the Arctic would not.

For future ships being built for service in polar waters, these are some of the considerations that must be taken into account when designing these ships.

2.2.4 Capacity, Scheduling and Other Marketing Factors

There are two market factors of interest for this project. First, the difference in cargo carrying capacity between different ice class ships and secondly, the difference in transit time between the southern and northern routes.

Capacity

Since a higher ice class of ship usually requires more power and increased ice strengthening the higher ice class ships either have to be larger and heavier than a lower ice class ship to carry the same amount of cargo, or they carry less cargo and are of roughly equivalent size. This creates a disadvantage for a higher ice class, as the ship will likely not have as large an earning capacity for it's size [Erikstad and Ehlers, 2012]. Thus, in order to be profitable, the ship will have to be able to deliver the faster and make more voyages per year compared to a lower ice class ship. This disparity between cargo carrying capacity is represented by the load factor which is a ratio of average load to total capacity [Stopford, 2009].

One company discussed the likelihood of ships to transit the northern routes laden both ways. They recognized that it is more likely that ships are fully laden one way and ballasting the other. Taking advantage of the NSR while ballasting saves the amount of time the ships are in ballast condition, in turn increasing their load factor. While shipping laden in the northern routes also saves time, the increase in time saved is of increased importance when in ballast conditions.

Scheduling

A major concern for companies evaluating the feasibility of the Arctic seaways is the seasonality of the routes. Most ships are restricted to transit between the months of July through to mid-November [Ministry of Transport of Russia, 2013]. Ice class and availability of icebreaker escorts are the biggest factors effecting an individual ships sailing window for the Arctic Seaways.

Practically, constructing a high ice class ship is expensive and thus most ships that wish to transit through the Arctic will be ice strengthened to an ice class usually equivalent to the Finnish Swedish Ice Class Rules (FSICR) 1A or 1A-Super designations [(NSR) Information Office, 2015]. This often reduces the sailing window of the lower ice class ships to less than five months.

Ships using the Arctic seaways will need to have their schedules adjusted to accommodate for five months of possible Arctic operation and seven months of strictly southern route operation. During the summer months the ships would be able to use the Arctic seaways as an alternative to southern routes, with route scheduling decided just before departure [Erikstad and Ehlers, 2012].

A higher ice class ship is able to navigate harsher ice conditions without icebreaker assistance compared to a lower ice class ship. It also can proceed faster than a lower ice class ship in mild ice conditions, allowing a higher ice class ship to navigate the northern routes both faster and for a longer season than the lower ice class ship. The transit time difference between the southern and northern routes and the lower and higher ice class ship needs to be accounted for as profit gained/lost per day of increase/decreased voyage time.

2.3 Ship Resistance in Ice

There are few numerical approaches to solving for ice resistance, unlike the availability of Computational Fluid Dynamic models for open water resistance. This leaves several empirical formulas, mostly derived from Baltic Sea ice measurements.
A ship's speed in ice, v_{ice}, is directly proportional to the total ice resistance, R_{ice}, or more accurately the net thrust, T_{net}, required to overcome the ice resistance. The total resistance in ice is calculated according to type of ice (level ice, channel ice, ridged ice etc.) and is dependant on the equivalent ice thickness h_{eq}. The relationship can be seen in Equation (2.1) which is used by Riska and Leiviskä [1997] and Kotovirta et al. [2009].

$$T_{net}(v_{ice}) = R_{ice}(v_{ice}, h_{eq}) = \Big(1 - \frac{1}{3}\frac{v_{ice}}{v_{ow}} - \frac{1}{3}(\frac{v_{ice}}{v_{ow}})^2\Big)T_{pull} \tag{2.1}$$

Where bollard pull is calculated as:

$$T_{pull} = Ke(P_s D_p)^{\frac{2}{3}} \tag{2.1a}$$

Ke = quality coefficient for bollard pull
P_s = propulsion power (kW)
D_p = propeller diameter (m)

Resistance in ice is heavily dependant on the ice regime, which is comprised of ice thickness, form and stage of development. There are various ways of obtaining this information, most commonly used are local ice measurements or satellite data. This information is passed to mariners in the form of ice charts.

2.3.1 International Ice Charts

Ice charts provide mariners with the necessary information about the ice regime to make informed operational decisions. Ice charts are usually provided by various meteorological institutes, like Canada's Ice Service or the Finnish Maritime Institute. The World Meteorological Organization (WMO) has standardized codes for displaying ice chart information, called the egg code depicted in Figure 2.1.

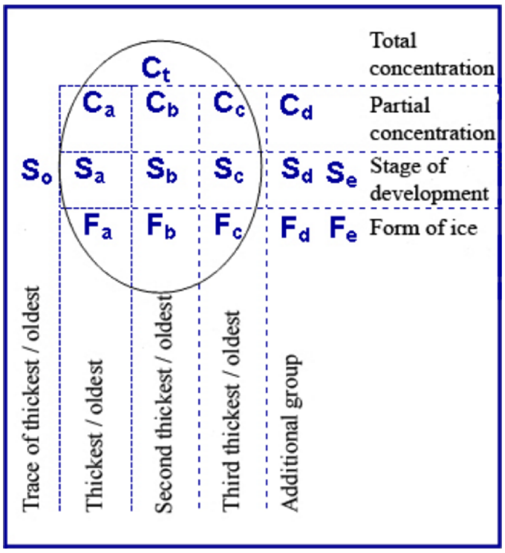

Figure 2.1: Egg Code Legend [Canadian Ice Service, 2016b]

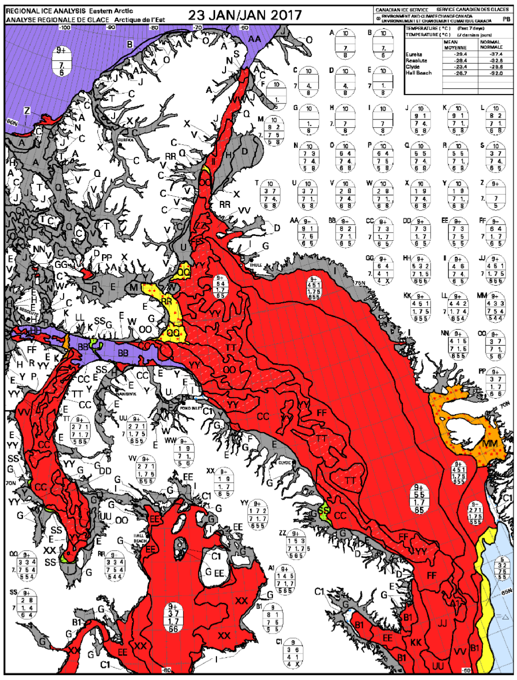

Figure 2.2: Western Arctic Ice Chart [Canada Ice Service, 2017]

The egg code provides the ice partial concentration, stage of development and form of ice that make up the ice regime in a defined area on the ice chart.
The concentration is shown in tenths starting from the thickest ice form on the left. The stage of development is an indicator of ice thickness as well as ice strength. Fresh water ice has the highest flexural strength followed by multi-year ice and first year ice respectively [Frederking,R. and Sudom,D., 2013]. The form of ice indicates the size of the ice floes, which can range from less than 2m to over 10km in width. The form also indicates if land ice is present.

2.3.2 Level Ice

According to WMO's Sea Ice Nomenclature [Joint Technical Commission for Oceanography and Marine Meteorology, 2014], level ice is defined as ice that has not been deformed. Level ice resistance can be calculated using the following equations developed by Riska and Leiviskä [1997].

$$R_i = C_1 + C_2 v \tag{2.2}$$

Where the constants are:

$$C_1 = \frac{f_1}{(2(\frac{T}{B}) + 1)} B L_{par} h_i + (1 + 0.021\phi)(f_2 B h_i^2 + f_3 L_{bow} h_i^2 + f_4 B L_{bow} h_i) \tag{2.2a}$$

and

$$C_2 = (1 + 0.063\phi)(g_1 h_i^{1.5} + g_2 B h_i) + g_3 h_i (1 + 1.2\frac{T}{B}) \frac{B^2}{\sqrt{L}} \tag{2.2b}$$

Table 2.2: Variables of Equation (2.2)[Riska and Leiviskä, 1997]

Variable	Description	Variable	Constant	Units
T	Ship Draught	f_1	0.23e3	$\frac{N}{m^3}$
B	Ship Maximum Breadth	f_2	4.58e3	$\frac{N}{m^3}$
L_{par}	Length of the Parallel Midbody	f_3	1.47e3	$\frac{N}{m^3}$
h_i	Level Ice Thickness	f_4	0.29e3	$\frac{N}{m^3}$
L_{bow}	Length of the Ship Bow	g_1	18.9e3	$\frac{\frac{N}{m}}{s*m^{1.5}}$
ϕ	Bow Angle	g_2	0.67e3	$\frac{\frac{N}{m}}{s*m^{1.5}}$
L	Ship Length	g_3	1.55e3	$\frac{\frac{N}{m}}{s*m^{1.5}}$
v	Ship Speed Effected by Ice			

2.3.3 Channel Ice

Channel ice has two distinct components, the consolidated ice layer which consists of broken ice blocks that have begun to freeze together, and the brash ice layer underneath this consisting of broken ice blocks. Thus channel ice resistance is treated as the summation of brash ice resistance and level ice resistance (for the consolidated layer) [Riska and Leiviskä, 1997].

$$\begin{aligned} R_{channelice} = {} & \frac{1}{2}(1-p)(\rho_w - \rho_i) g h_f^2 K_p \Big(\frac{1}{2}\frac{h_m}{2 * h_f}\Big)^2 \Big[B + 2h_f\Big(cosd(\delta) - \frac{1}{tand(\psi)}\Big)\Big] \\ & \Big[\mu_h cosd(\alpha) + sind(\psi) sind(\alpha)\Big] + (1-p)(\rho_w - \rho_i) g K_o \mu_h L_{par} h_f^2 + \\ & (\rho_w - \rho_i) g \Big(L\frac{T}{B^2}\Big)^3 \frac{h_m A_{wf} v}{L_{par} g} \end{aligned} \tag{2.3}$$

Where

$$h_f = h_m + \frac{B}{2}tand(\gamma) + \Big[tand(\gamma) + tand(\delta)\Big]\sqrt{\frac{B\big(h_m + \frac{B}{4}tan(\gamma)\big)}{tan(\gamma) + tan(\delta)}} \tag{2.3a}$$

$$K_p = \frac{1 + sin(\Phi)}{1 - sin(\Phi)} \tag{2.3b}$$

$$K_o = \frac{\nu}{1 - \nu} \tag{2.3c}$$

Table 2.3: Variables of Equation (2.3)[Riska and Leiviskä, 1997]

Variable	Description
ρ_{water}	Density of Water
ρ_{ice}	Density of Ice
K_p	Coefficient of Passive Stress
K_o	Coefficient of Lateral Stress at Rest
δ	Slope Angle of Brash Ice Side Wall = 22.6^o
g	Gravitational Constant
$(1-p)$	Brash Ice Frictional Constant = 0.8
μ_h	Coefficient of Dynamic Friction between Hull and Ice = 0.15
h_f	Brash Ice Thickness Displaced at Bow
h_m	Brash Ice Thickness at the Middle of the Channel = 1m
α	Waterline Angle
ψ	Flare Angle: $\arctan(\frac{tan(\phi)}{sin(\alpha)})$
A_{wf}	Waterline Area
γ	Parallel Body Ice Angle (Figure 2.3)
Φ	Internal Friction Angle = 50^o
ν	Poissons Ration for Ice = 0.33

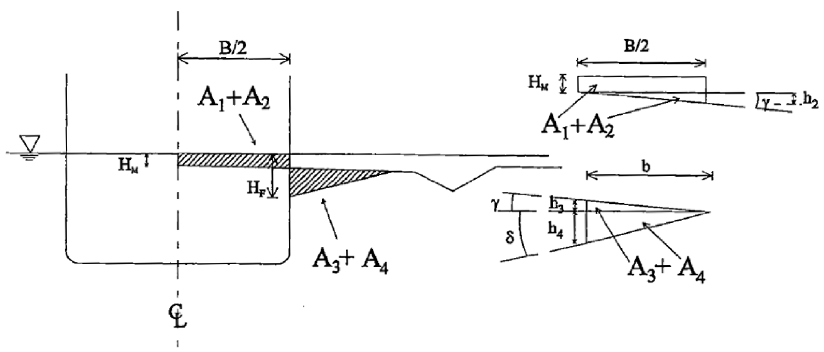

Figure 2.3: Angles for Calculating h_f [Riska and Leiviskä, 1997]

2.3.4 Ridge Resistance

Ice ridge resistance is the most involved component of ice resistance calculations, however it is also one of the most important [Riska and Valkonen, 2014]. Kotovirta et al. [2009] presented the following method for calculating resistance in ridged ice. It is derived from a summation of level ice resistance (See Section 2.3.2) and ridged ice resistance.

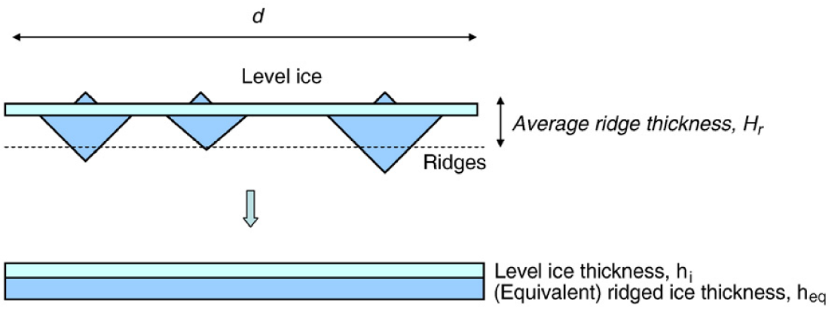

Figure 2.4: Equivalent Ice Thickness in Ridged Ice [Kotovirta et al., 2009]

To solve for the ridged ice resistance, an equivalent ice thickness, h_{eq}, is used. This effectively flattens the ridges to an average ice thickness for the sail and keel portion of the ridge, while the level ice thickness is used for the consolidated layer of the ridge, this is shown in Figure 2.4. The equivalent ridged ice thickness is calculated as:

$$h_{eq} = \frac{\mu_s H_r^2}{tan(\kappa} \tag{2.4}$$

Table 2.4: Variables of Equation (2.4)[Kotovirta et al., 2009]

Variable	Description
μ_s	Expected number of ridges per meter
κ	Keel Angle (20^o)
H_r	Average ridge thickness

$$R_{ice} = R_{levelice} + R_{ridge} = (C_1 + C_2 v) + (C + Dv) \tag{2.5}$$

Where:

$$C = 4C_3 h_{eq}^2 (B + 2C_{psi} h_{eq})(\mu \cos(\phi) + \sin(\psi)\sin(\alpha)) + C_4 L_{par} h_{eq}^2 \tag{2.5a}$$

$$D = C_5 (L \frac{T}{B^2})^3 h_{eq} A_{wf} (gL)^{-0.5} \tag{2.5b}$$

C_{psi} = 0.047 ψ - 2.115 > 0
C_1 = See Section 2.3.2
C_2 = See Section 2.3.2
C_3 = 850 $\frac{N}{m^3}$
C_4 = 42 $\frac{N}{m^3}$
C_5 = 1300 $\frac{N}{m^3}$

2.3.5 Open Water Resistance

Hollenbach's method can be used to break open water resistance into three components for ship resistance calculations: residual resistance, frictional resistance, and resistance allowance.

$$R_{ow} = R_R + R_F + R_A \tag{2.6}$$

Residual Resistance:
[Molland, 2011] The residual resistance accounts for appendage resistance and is calculated as follows:

$$R_R = \frac{1}{2}\rho_w(BT/10)v_{ow}^2 C_R \tag{2.7}$$

Where:

$$C_r = Cr_{stand}Cr_{Fn_{crit}}k_L\left(\frac{T}{B}\right)^{b_1}\left(\frac{B}{L}\right)^{b_2}\left(\frac{L_{os}}{L_{wl}}\right)^{b_3}\left(\frac{L_{wl}}{L}\right)^{b_4}\left(\frac{1+(T_a-T_f)}{L}\right)^{b_5}\left(\frac{D_p}{T_a}\right)^{b_6}$$
$$(1+N_{rudd})^{b_7}(1+N_{brac})^{b_8}(1+N_{boss})^{b_9}(1+N_{thruster})^{b_{10}} \tag{2.7a}$$

$$Cr_{stand} = c_{11} + c_{12}Fn + c_{13}Fn^2 + C_B(c_{21} + c + 22Fn + c_{23}Fn^2) +$$
$$C_B^2(c_{31} + c_{32}Fn + c_{33}Fn^2) \tag{2.7b}$$

$$Cr_{Fn_{crit}} = max(1, (Fn/Fn_{crit})^{f_1}) \tag{2.7c}$$

$$k_L = e_1 L^{e_2} \tag{2.7d}$$

$$L_{fn} = L + \frac{2}{3}(L_{os} - L) \tag{2.7e}$$

$$Fn = \frac{v_{ow}}{\sqrt{9.81L_{fn}}} \tag{2.7f}$$

$$Fn_{crit} = d_1 + d_2C_B + d_3C_B^2 \tag{2.7g}$$

Table 2.5: Residual Resistance Coefficients [Molland, 2011]

Coefficient	**Value**	**Coefficient**	**Value**
b_1	-0.3382	c_{11}	-0.5742
b_2	0.8086	c_{12}	13.3893
b_3	- 6.0258	c_{13}	90.596
b_4	-3.5632	c_{21}	4.6614
b_5	9.4405	c_{22}	-39.721
b_6	0.0146	c_{23}	-351.483
b_7	0	c_{31}	-1.14215
b_8	0	c_{32}	-12.3296
b_9	0	c_{33}	459.254
b_10	0	f_1	0.86607
d_1	0.854	e_1	2.1701
d_2	-1.228	e_2	-0.1602
d_3	0.497		

Frictional Resistance:
[Matusiak, 2008] The frictional resistance is calculated using the ITTC-57 frictional coefficient correlation line, as follows:

$$R_F = \frac{1}{2}\rho_w S_{tot} v_{ow}^2 C_F \tag{2.8}$$

$$S_{tot} = kL(B + 2T) \tag{2.8a}$$

$$k = a_0 + a_1\frac{L_{os}}{L_{wl}} + a_2\frac{L_{wl}}{L} + a_3C_B + a_4\frac{B}{T} + a_6\frac{L}{T} + a_7\frac{T_a - T_f}{L} + a_8\frac{D_p}{T} + k_{rudd}N_{rudd} + k_{brac}N_{brac} + k_{boss}N_{boss} \tag{2.8b}$$

$$C_F = \frac{0.075}{(log_{10}(Re) - 2)^2} \tag{2.8c}$$

$$Re = v_{ow}\frac{L}{v} \tag{2.8d}$$

Table 2.6: Frictional Resistance Coefficients [Matusiak, 2008]

Coefficient	**Value**	**Coefficient**	**Value**
a_0	-0.6837	a_6	-0.0045
a_1	0.2771	a_7	-0.4798
a_2	0.6542	a_8	0.0376
a_3	0.6422	k_{rudd}	0.0131
a_4	0.0075	k_{brac}	-0.0030
a_5	0.0275	k_{boss}	-0.0061

Resistance Allowance:
[Hänninen, 2015] Resistance allowance accounts for the surface roughness. The value of the resistance allowance coefficient C_A is based on the length of the ship.

$$Ra = \frac{1}{2}\rho_w S_{tot} v_{ow}^2 C_A \tag{2.9}$$

Where:

$$Ca = 0.0004$$

$$\upsilon = 1.191E - 6$$

$$C_B = \frac{\Delta}{L_{wl}BT}$$

2.4 POLARIS: Polar Operational Limit Assessment Risk Indexing System

POLARIS is used to fulfill the route or voyage planning aspect of the Polar Code. It takes into account that even though all ships are sailing in polar water there are ships of different ice classes travelling through different types of ice regimes, with or without icebreaker assistance. All of these factors are taken into consideration when calculating the Risk Index Outcome (RIO) for a voyage segment.

2.4.1 Development of POLARIS

The Polar Code states that: "In order to establish procedures or operational limitations, an assessment of the ship and its equipment shall be carried out" [IMO, 2016a, Part I-A, Section 1.5]. This is further elaborated on in Part I-B Section 2 which calls for "a model to analyze risk ... and determine acceptability" [IMO, 2016a]. At the MSC convention 93, an informal working group, coordinated by IACS, was created to put forth a proposal for how to set operational limitations on ice navigation to be included as an amendment for part I-B section 2.1 of the Polar Code. The work group consisted of delegates from Canada, Denmark (Greenland), Finland, Russia and Sweden [Canada et al., 2014].

There were five important features that the working group included in this amendment. They first wanted to use equivalent ice class designations from IACS Polar Classes and the FSICR that were consistent with the ice class references used in the existing draft of the Polar Code. Secondly, they wanted to use WMO nomenclature for ice type definitions that are found on international ice charts. Thirdly, they wanted to consider both partial ice concentrations and ice decay, which takes into account the existence of multiple ice types in various concentrations as well as reduced risks due to ice strength reduction in the summer months. Lastly the working group wanted to account for the different risk profile associated with ships under icebreaker escorts.

At the MSC 94 meeting the work group presented their proposal, called the Polar Operational Limit Assessment Risk Indexing System or POLARIS. The system, true to its creators wishes, considers the operational limitations of ships transiting through ice covered waters. Paired with other requirements outlined in the Polar Code, POLARIS provides a method of route planning that can be directly linked to ship speed and thus transit costs [International Association of Classification Societies, 2014].

2.4.2 Route Planning with POLARIS

The RIO is a calculated value, based on ice concentration and ice type, that POLARIS uses to assess operational limitations in ice. It is calculated as:

$$RIO = (C_1 * RIV_1) + C_2 * RIV_2) + C_3 * RIV_3) + ...(C_n * RIV_n) \tag{2.10}$$

Where:	$C_1...C_n$	are concentrations (in tenths) of the different ice types within the encountered ice regime
	$RIV_1...RIV_n$	are the respective Risk Index Values

2.4.3 Ice Regime

Ice types, thickness and concentrations are classified on international ice charts according to WMO nomenclature. The egg code, as seen in Figure 2.1 is shown on the ice chart and provides all the necessary information required to calculate the RIO value for each section of the voyage. Concentration from the egg code is used as the concentration of each ice regime in the RIO calculation. The RIV is calculated using the ice thickness from the Stage of Development and the ice regime is determined from the Form of Ice and Stage of Development.

2.4.4 Risk Index Values

Once the number of ice types and their corresponding partial concentrations (ice regime) have been identified, the next step is to calculate the Risk Index Values (RIV) for each ice type. This is done using Table 2.7. There are RIV's for both summer and winter conditions, however the winter conditions are to be used at all time unless ice decay has been observed by an advanced level qualified Master. The RIV for each ice type differs for the ice class of the ship, the higher the ice class of the ship the higher the RIV.

Table 2.7: Risk Index Values [International Association of Classification Societies, 2014]

Ice Class	**PC4**		**FS1A**	
Ship Category	**A**		**C**	
Conditions	Winter	Summer	Winter	Summer
Ice Regime	**RIV**			
Ice Free	3	3	3	3
New Ice	3	2	3	2
Grey Ice	3	2	3	2
Grey White Ice	3	2	3	2
Thin 1st Yr Ice, 1st Stage	2	1	2	1
Thin 1st Yr Ice, 2nd Stage	2	0	2	0
Medium 1st Yr Ice, 1st Stage	2	-1	2	0
Medium 1st Yr Ice, 2nd Stage	2	-2	2	-1
Thick 1st Yr Ice	1	-3	1	-2
Second Year Ice	0	-4	0	-4
Light Multi Year Ice	-1	-4	-1	-4
Heavy Multi Year Ice	-2	-4	-2	-4

2.4.5 Risk Index Outcome Evaluation Criteria

With the various ice types, partial concentrations and corresponding RIV's identified the RIO can be calculated. The RIO_{ship} values from Table 2.8 are used when determining the operational limitations of an unescorted ship. If the ship is being escorted by an icebreaker, the RIO calculation changes depending on the beam of the ship in relation to the icebreakers track. If the icebreakers track is narrower than the escorted ships beam then the RIO calculation ignores the icebreakers effects. If the track of the icebreaker is larger than the beam of the escorted ship, four RIO's are to be calculated:

1. The icebreaker evaluates a RIO based on the RIV's and ice regime that the icebreaker would encounter if the icebreaker was operating independently.

2. The icebreaker evaluates a RIO based on the RIV's and ice regime that the escorted ship would encounter if operating independently, with +10 added to the evaluated RIO to account for being escorted.

3. The escorted ship evaluates a RIO based on the RIV's and ice regime that the escorted ship would encounter if operating independently, with +10 added to the evaluated RIO to account for being escorted. Ice charts and information from the icebreaker is used to calculate the RIO.

4. The escorted ship evaluates a RIO based on the RIV's considering an ice regime that includes the icebreaker's track.

The $RIO_{escorted}$ values from Table 2.8 are to be used when determining the operational limitations of the icebreaker and escorted ship [International Association of Classification Societies, 2014].

Table 2.8: Risk Index Outcome Evaluation Criteria [International Association of Classification Societies, 2014]

Unescorted Ship, RIO_{ship}		
Ship Category	**B (PC4)**	**C (FS1A)**
$RIO \geq 0$	Operation Permitted	Operation Permitted
$-10 \leq RIO < 0$	Limited Speed (5 Knots) Operation Permitted	Operation Subject to Special Consideration
$RIO < -10 \geq 0$	Operation Subject to Special Consideration	Operation Subject to Special Consideration

Icebreaker Escorted Ship, $RIO_{escorted}$		
Ship Category	**B (PC4)**	**C (FS1A)**
$RIO \geq 0$	Operation Permitted	Operation Permitted
$-10 \leq RIO < 0$	Limited Speed (5 Knots) Operation Permitted	Limited Speed (3 Knots) Operation Permitted
$RIO < -10 \geq 0$	Operation Subject to Special Consideration	Operation Subject to Special Consideration

Chapter 3

Cost Benefit Model

The Cost-Benefit Model is constructed in Matlab using several interconnected functions to run different scenarios. The CBM is designed to illustrate the cost and time differentials between the northern and southern routes in order to assess the feasibility of the routes in comparison to each other. This section outlines the setup and functions of the CBM, describing it's inputs, decision matrix, calculations and outputs.

3.1 Ship Characteristics

The cost benefit analysis is centered around exploring the differences between a ice class FS1A ship and a PC4 ship as defined by IACS. Table 3.1 shows the relevant ship parameters used in the model.

Two ships are used for the simulation to capture the differences in construction between ships that are built to meet different ice class requirements as well as being designated for use in the Arctic. M/V Nunavik is a PC4 handymax bulk carrier operated by Fednav Ltd. and M/V Nordic Barents is a FS1A handymax bulk carrier, operated by Nordic Bulk Carriers A/S. These two ships have both previously transited through the Arctic and were selected to provide a realistic comparison between different ice class ships. In this model the M/V Nunavik's bubbling system will be ignored in the ice resistance calculations.

Table 3.1: Ship Model Characteristics [IHS Global Limited, 2017]

Variable	Characteristic	FS1A	PC4	Units
L	Overall Length	190.0	189	m
B	Breadth	30.5	26.6	m
T	Draught	11.5	11.8	m
L_{PP}	Length Between Perpendiculars	183	170	m
L_{bow}	Length of the Ship Bow	19	38	m
L_{par}	Length of the Parallel Mid-body	133	126	m
Ps	Ships Power	11,475	21,770	kW
Dp	Propeller Diameter	5.5	6.5	m
v_{ow}	Open Water Speed	7.2	6.69	m/s
ϕ	Stem Angle	50	28	deg
α	Waterline Angle	38	19	deg
A_{wf}	Entrance Waterplane Area	290	502	m^2
DWT	Deadweight	43,732	31,754	t
NT	Net Tonnage	13,844	8,841	t
GT	Gross Tonnage	27,078	22,622	t
Δ	Displacement	53,618	44,000	t
$SFOC$	Specific Fuel Oil Capacity	174	171	g/kWh
	Crew	14	12	
	Officers	9	13	

3.2 Routes

There are two route choices used in the simulation.The first between Kokkola, Finland and Shanghai, China transiting through either the SCR or the NSR. The second between Kokkola, Finland and Vancouver, Canada transiting through either the PCR or the NWP. Table 3.2 shows the distance in nautical miles between the ports depending on what route is taken.

Table 3.2: Shipping Route Alternative Distances (in nautical miles) [Veson, 2017]

Route	NWP	NSR	SCR	PCR
Kokkola-Vancouver	8,103	7,230	16,772	10,035
Kokkola-Shanghai	9,251	8,375	11,960	14,545

3.2.1 Northern Sea Route

The NSR is divided into seven sections based on areas with consistently similar ice regimes as shown in Table 3.3. This division is based on the division provided by Riska and Salmela [1994] in their analysis of ice conditions along the NSR. The ice data available covers 2,760nm of the total route length of 8,375nm between Kokkola and Shanghai. The transit model assumes that the rest of the route is open water, or the concentration of ice coverage is low enough that the ship can reasonably navigate in ice free water.

Table 3.3: Sections and Distances for the NSR [Riska and Salmela, 1994]

Section	Name	Distance (nm)
I	Kokkala to Pechora Sea	2615
II	Pechora Sea	180
III	Western Kara Sea	320
IV	Eastern Kara Sea	540
V	Laptev Sea	580
VI	Western East Siberian Sea	440
VII	Eastern East Siberian Sea	310
VIII	Chukchi Sea	390
IX	Bering Strait to Shanghai	3000
	Total	8375

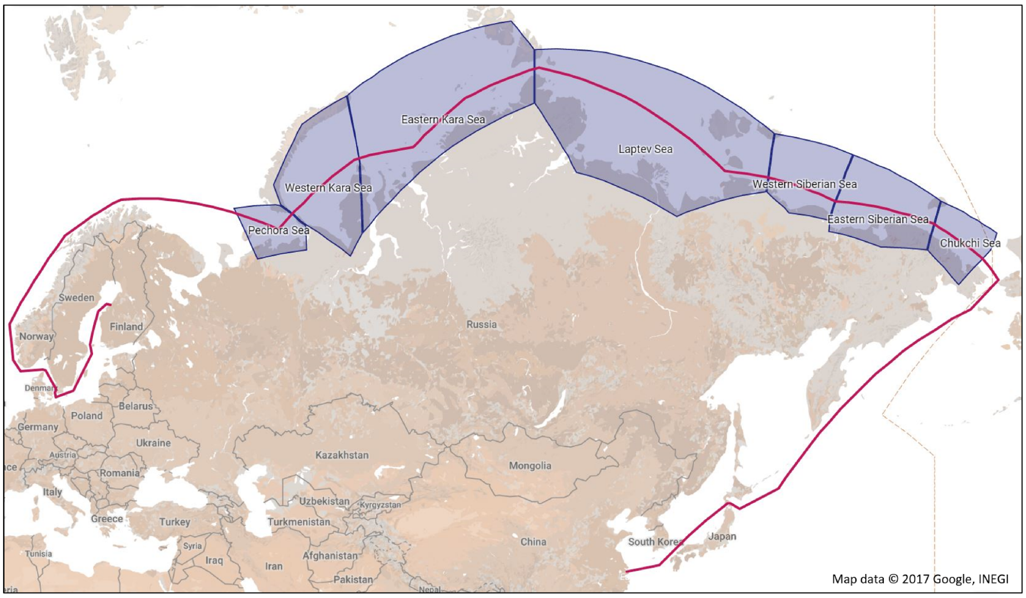

Figure 3.1: Northern Sea Route [Riska and Salmela, 1994] (Compiled by Author with Google MyMaps)

3.2.2 Suez Canal

The Suez Canal is broken into three sections, as shown in Table 3.4, for the purpose of the transit simulation: I before the Suez Canal, II the passage through the Suez Canal and III after the Suez Canal. Section I & III are assumed to be transited at open water velocity at all times. Section II is transited according to the velocity restrictions dictated by the Suez Canal Authorities as well as taking into account expected time delays through the canal.

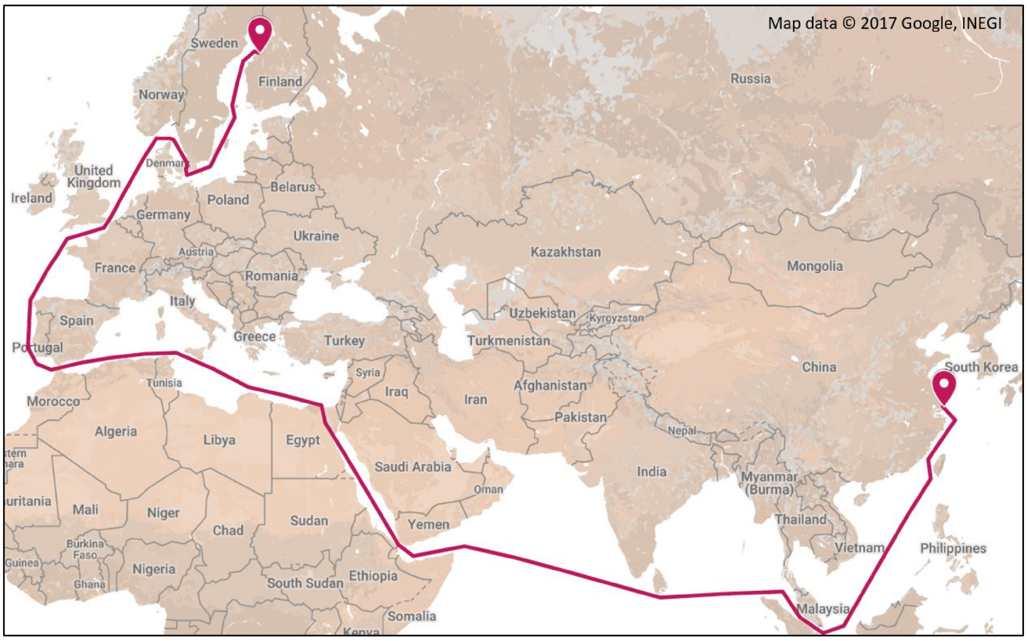

Figure 3.2: Suez Canal Route (Compiled by Author with Google MyMaps)

Table 3.4: Sections and Distances for the SCR [Veson, 2017]

Section	**Name**	**Distance (nm)**
I	Kokkola to Suez Canal (Port Said)	4,761
II	Port Said to Port Tewfik	86
III	Port Tewfik to Shanghai	7,113
	Total	11,960

3.2.3 Northwest Passage

There are several routes that can be taken through the islands of the Canadian Archipelago. The route chosen for this analysis was selected as it is the most direct, avoids the build up of old ice in the M'Clure Strait and has a depth suitable for larger ships [Lu et al., 2014]. Figure 3.3 shows the individual stages of the NWP route that are considered to be ice covered in this analysis. The remaining distance between Kokkola and the entrance to Baffin Bay as well as the distance between the Beaufort Sea and Vancouver is considered to be ice free.

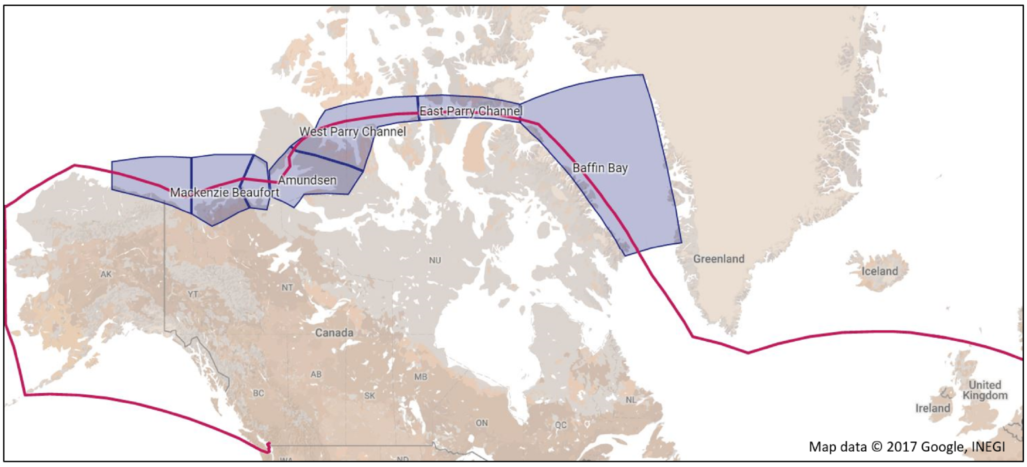

Figure 3.3: Northwest Passage Route through the Canadian Archipelago [Canadian Ice Service, 2016c] (Compiled by Author with Google MyMaps)

Table 3.5: Sections and Distances for the NWP [Veson, 2017]

Section	Name	Distance (nm)
I	Kokkola to Baffin Bay	3,106
II	Baffin Bay	742
III	Eastern Parry	263
IV	Western Parry	427
V	Amundsen	186
VI	Amundsen Mouth	70
VII	Beaufort Sea: Mackenzie	195
VIII	Beaufort Sea: Alaska	400
IX	Beaufort Sea to Vancouver	2,714
	Total	8103

3.2.4 Panama Canal

This project assumes the use of the old Panama Canal locks only, as the ships analyzed are relatively small and have no need to use the larger, more expensive Neo-Panamax locks. Like the SCR the PCR is broken into three sections, as shown in Table 3.6, I before the Panama Canal locks, II is the transit through the Panama Canal and III is the transit from the Panama Canal to Vancouver. Restrictions on velocity and expected time delays are taken into account, as they are through the Suez Canal.

Figure 3.4: Panama Canal Route (Compiled by Author with Google MyMaps)

Table 3.6: Sections and Distances for the PCR [Veson, 2017]

Section	**Name**	**Distance (nm)**
I	Kokkola to Panama Canal	5,941
II	Panama Canal	94
III	Panama Canal to Vancouver	4,000
	Total	10,035

3.3 Ice Data

As can be seen in Figure 3.5 egg code ice data (see Section 2.3.1) can be used to find most of the ice parameters necessary to construct a model to predict ship speed based on ice conditions and the POLARIS operational limitations.
An ice input string in egg code format includes the following variables from Figure 3.5:

$$Ct, Ca, Cb, Cc, Cd, Sa, Sb, Sc, Sd, Se, Fa, Fb, Fc, Fd, Fe$$

Ice data can be collected from each egg code ice regime encountered on the vessels intended voyage. Depending on the size of the areas covered by each egg code, the number of legs will vary. This method of obtaining ice data works for route planning a single voyage, however is very time consuming for constructing a yearly average for a route comparison analysis.

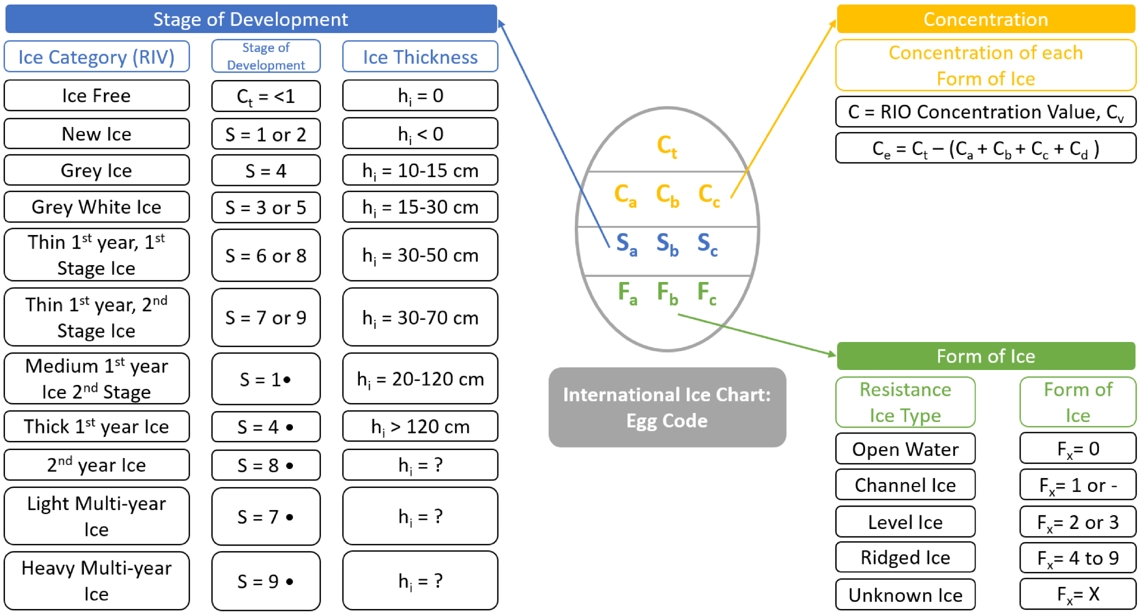

Figure 3.5: Speed Model Variables Derived from Egg Code Data

For this reason egg code data, from individual ice charts, is not used in the ship speed simulation. Instead monthly averages from two different sources with different variables was collected for the NSR and the NWP. Since the ice data variables are presented differently in the two sources, different assumptions were made when the ice data was compiled into egg code form. The CBM accepts ice data as a vector for each leg consisting of the total concentration, concentrations of ice regimes a through d, the stages of developments corresponding to the concentrations and the forms of ice also corresponding to the concentrations. The stages of development and forms of ice are entered as numerals corresponding to the regimes conditions, as shown in Figure 3.5. The ridge thickness and distance for each leg is also input in the ice data file.

3.3.1 Northern Sea Route

Ice data for the NSR is not as publicly available as data for the NWP. Riska and Salmela [1994] paper on "ice conditions along [the] north-east passage" gives ice thickness, ice concentration for first year and multi-year ice, and ridge sail heights for seven sections along the Northeast Passage (NEP) which is the part of the NSR from the Pechora Sea to the Bearing Strait. The ice data for the NSR can be found in Appendix A.
POLARIS requires that the stage of development of ice is known. Since the stage of development is not explicitly stated in the NSR ice data, several assumptions were made:

- First year ice thickness was used to classify stage of development from new ice to thick first year ice.

- Multi-year ice thickness was assumed to always have a heavy multi year stage of development as ice thickness was not given, only ice concentration.
- Form of ice was assumed to be ridged ice for the whole transit, with the ridge thicknesses coming from the data set.

3.3.2 Northwest Passage

The Government of Canada's Ice Service has publicly available historical ice data that can be downloaded directly from their website. Ice graphs can be compiled for set time periods and regions. A data set was compiled consisting of monthly averages for ice data from 2006-2016. The ice data provided consists of the total ice concentration, first year, old, young and new ice concentrations. The ice data for the NWP can be found in Appendix A. On the NWP data the following assumptions were made:

- Form of ice was assumed to be ridged ice for the whole transit.
- The ridge thickness is assumed to be uniform for each leg.

3.4 Ship Velocity Model

3.4.1 Calculation Routine for the Northern Routes

This section describes the calculation routines of the speed simulation model in ice for a ship on the northern routes. The routine calculates three outputs: The total volume of fuel consumed on the journey, the time the transit took in hours and the number of days an icebreaker was needed, according to POLARIS operational limitations.

Volume of fuel is calculated as follows:

$$V_{fuel} = \frac{SFOC}{\rho_{fuel}} * t * P \tag{3.1}$$

P = power rating of the ship in kW
ρ_{fuel} = density of fuel in g/m^3
SFOC = Specific Fuel Oil Capacity of the ships engine in g/kWh
t = time of transit in hours

Open Water Legs

For both the NSR and NWP the first and last legs of their transits are in open water. It is assumed that the ship is able to travel at full open water speed (v_{ow}) for the entire distance (d) of these legs encountering only ice free waters. The CBM also calculates a leg as open water if the total concentration value from the ice data is zero. Time of transit (t) and open water power (P_{ow}) for use in Equation (3.1) are calculated as follows:

$$t = \frac{d}{v_{ow}} \tag{3.2}$$

$$P_{ow} = R_{ow} * d_{ow} \tag{3.3}$$

Ice Covered Legs

For each ice covered leg the ship speed model goes through an iteration that determines the ships speed, volume of fuel consumed and number of days an icebreaker escort is required.

1. Ice data, in egg code format, is retrieved corresponding to the route and month requested.

2. The total concentration (Ct) is read and if it equals zero the open water speed calculation from above is performed. The iteration for this leg ends with speed as open water speed, fuel consumed as calculated in section 3.4.1 and icebreakers escort days as zero.

3. If Ct does not equal zero the rest of the egg code data is read & stored and ice thicknesses is assigned to each stage of development according to the parameters outlined in Table 3.7.

Table 3.7: Stage of Development Relationship to Ice Thickness [Canadian Ice Service, 2016b]

Ice Regime	**Stage of Development (S_x)**	**Ice Thickness cm**
New	1	5
Nilas	2	10
Young	3	10-30
Grey	4	10-15
Grey-white	5	15-30
First-year	6	30
Thin first-year	7	30-70
First stage thin first-year	8	30-50
Second stage thin first-year	9	50-70
Medium first year	10	70-120
Thick first year	40	120-200
Old	70	200-500
Second-year	80	200
Multi-year	90	200-500
Ice of Land Origin	100	300-800

4. The resistance (and velocity) in ice calculation type (ridge, channel, or level) is assigned to each form of ice as outlined in Table 3.8.

Table 3.8: Form of Ice Relationship to Ice Resistance Calculation Method [Canadian Ice Service, 2016b]

Ice Regime	**Form of Ice (F_x)**	**Calculation Routine**
Pancake	0	Open Water
Small Ice Cake	1	Channel
Ice Cake	2	Level
Small Floe	3	Level
Medium Floe	4	Ridge
Big Floe	5	Ridge
Vast Floe	6	Ridge
Giant Floe	7	Ridge
Fast Ice	8	Ridge
Icebergs, growlers	9	Ridge

5. The velocity and resistance in ice for each ice regime within a leg are calculated according to ice form and averaged. The ships true velocity is then determined by the concentration of ice coverage according to the formula outlined in Kotovirta et al. [2009]:
$C_{70} = \frac{7}{10}$ Concentration and $C_{90} = \frac{9}{10}$ Concentration

$$\mathrm{v}=\left\{ \begin{array}{cc} v_{ow} & C \leq C_{70} \\ \frac{(C_{90}-C)v_{ow}+(C-C_{70})v_{ice}}{C_{90}-C_{70}} & C_{70} < C < C_{90} \\ v_{ice} & C \geq C_{90} \end{array} \right\}$$

6. The next stage is calculating the operational limitations on the transit of the leg according to the POLARIS outline (see Section 2.4). First the RIO value and from this the maximum allowable speed for the ship in the defined ice conditions are determined.

7. If the RIO value allows for *independent operation*, and the calculated RIO velocity is above zero (see Section 2.4), this velocity is used for the calculation of time for the transit of the leg, the volume of fuel consumed is calculated as per Equation (3.1) and the number of icebreaker days is zero.

8. If *independent operation is not permitted* by POLARIS an icebreaker is called.

9. When an icebreaker has been called the ship calculates its RIO value under escort and the PC2 escort icebreaker calculates it's RIO value as if operating independently in the given ice regime. The smaller of these two RIO values is used to determine the operational limitations.

10. If operation is allowed, the ships velocity and resistance is calculated in the channel ice behind the icebreaker. This is done by using the ice data for that leg, but assuming that the ship only experiences brash ice. If there are operational speed limitations, the ships speed is taken as the minimum of the limited speed and speed in the ice channel. The total time of transit has an added delay of (between 0 and 10 hours [Canadian Coast Guard, 2016]) to account for time lost waiting for an icebreaker to come assist the ship.

11. Should the ship still not be permitted to operate under POLARIS limitations even with an icebreaker escort, a randomly selected time delay (between 1 and 24 hours) for bad conditions is added to the time of transit and the ships velocity is taken as the lower of 3 knots or speed in channel ice for the duration of that leg.

3.4.2 Calculation Routine for the Southern Routes

The calculation routine for the southern routes is the same as that of the open water calculation from the northern routes routine, see eq. (3.1), with a few exceptions of speed and queuing delays through the canal sections.

Suez Canal

The Suez Canal has a speed requirement of 14km/h which is adhered to for the canals length of 86 nautical miles. The Suez Canal queuing system is designed to reduce the total transit time between time of arrival at the canal to departure to under 40 hours [Griffiths, 1995]. The actual transit time though the canal itself takes on average 11.4 hours. To account for this queuing time, the cost benefit model randomly assigns a queuing delay between 0 and 28 hours to the total transit time of the SCR.

Panama Canal

The transit through the Panama Canal takes on average 8-10 hours with an unreserved ship encountering a queuing delay of anywhere between 24-28 hours [Laih and Sun, 2013]. The transit time and queuing delay are both randomly selected, between the above parameters, for the Panama Canal section of the PCR.

3.5 Economic Feasibility Model

As seen in Section 2.2 there are eight sections, which can be divided into three categories that are considered in this model. Figure 3.6 shows a simplified flowchart depicting the flow of inputs (shown in green) through the model to the final output of voyage cost.

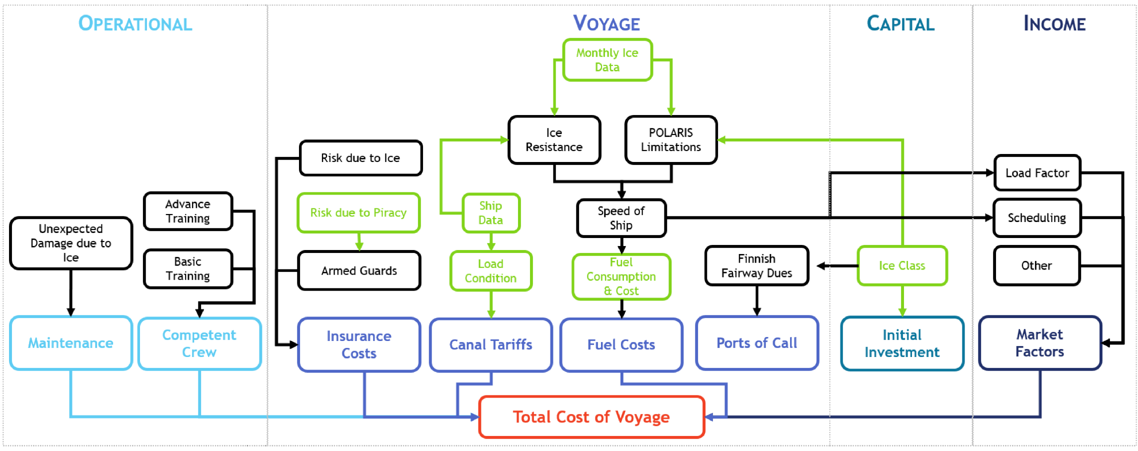

Figure 3.6: Schematic of Voyage, Operational and Capital Costs in the CBM

The following sections discuss the inputs and assumptions made within the model as setup for the research simulations.

3.5.1 Fuel Type & Consumption

Fuel consumption is based on the volume of fuel consumed which is calculated by the transit model outlined in Section 3.4. The total cost of fuel used is found by summing the volume of fuel consumed across all legs and multiplying by the fuel cost per ton.

Table 3.9: Fuel Prices [Bunker, 2017]

Fuel	Cost (USD/t)
NDF	810
IFO (North Routes)	600
IFO (Panama)	620
IFO (Suez)	725

Fuel type directly effects the cost of fuel. Fuels with lower freezing points like NDF are better suited for winter conditions however they are more expensive than MDO or IFO. Table 3.9 shows the cost of fuel used in the simulation. Each ship is assumed to always use IFO for all southern routes, with the ships bunkering at Panama Canal or Suez Canal. The northern routes can use either NDF or IFO depending on the simulation inputs, the northern route ships bunker in northern Europe. The regional difference in fuel prices is reflected in fuel prices as shown in Table 3.9.

3.5.2 Insurance

Insurance costs considered in the model are limited to any costs that are above and beyond those required for everyday operation in ice free, non-dangerous waters. The PCR is considered to have no additional insurance needed, as piracy is very low in the area and the waters are ice free. The SCR is subject to an additional insurance fee for piracy risk, the risk level can be set to high, medium or low within the simulation. The NSR requires both additional risk insurance due to ice and additional certification and charts. The NWP only requires additional risk insurance due to ice.

Table 3.10: Additional Insurance Expenses for SCR and NSR [Compiled from Company Interviews]

Additional Insurance Costs SCR (High Piracy Risk)	**Cost in USD**
Armed Guard	100 000
Additional Risk	50 000
Total SCR	*150 000*
Additional Insurance Costs SCR (Medium Piracy Risk)	**Cost in USD**
Armed Guard	80 000
Additional Risk	30 000
Total SCR	*110 000*
Additional Insurance Costs SCR (Low Piracy Risk)	**Cost in USD**
Armed Guard	50 000
Additional Risk	10 000
Total SCR	*60 000*
Additional Insurance Costs NSR	**Cost in USD**
Certifications, Charts, Other	10 000
Additional Risk Due to Ice	50 000
Total NSR	*60 000*
Additional Insurance Costs NWP	**Cost in USD**
Additional Risk Due to Ice	50 000
Total NWP	*50 000*

3.5.3 Canal Tolls & Transit Tariffs

The canal tariffs for each of the southern routes was calculated for both the ballast and laden conditions. The northern routes do not differentiate price for loading condition. The NSR is known to have an official and a negotiated tariff price that closly mimics the Suez Canal toll. Scenarios can consider either a negotiated or non-negotiated NSR tariff price.
Canada does not charge a tariff for transiting through the NWP, however should the

vessel need icebreaker support there is a flat fee, that is reduced dependant upon the ice class of the ship, charged each time an icebreaker is needed. [Minister of Fisheries and Oceans, 2013]. The CCG says that Arctic icebreaker support is at most 10 hours away; however there was some skepticism from the companies interviewed about the accuracy of the CCG's icebreaker response times in the Arctic.

Table 3.11: Canal Tariffs [Suez Canal Authority, 2008a; Panama Canal Authority, 2017; Northern Sea Route Information Office, 2013]

Suez Canal	**FS1A**	**PC4**
Laden	$64,970	$46,267
Ballast	$55,254	$39,343
Panama Canal (Old Locks)	**FS1A**	**PC4**
Laden	$166,719	$118,954
Ballast	$137,226	$95,528
Northern Sea Route	**FS1A**	**PC4**
Negotiated Base Tariff	$64,970	$46,267
Non-Negotiable Tariff	$98,078.61	$80,295.95
Icebreaker Fee Addition per Leg	+$24,518.50	+$20,074.95
Northwest Passage	**FS1A**	**PC4**
Icebreaker daily fee	$2,015	$2,015

3.5.4 Ports of Call

For this project the costs associated with ports of call is exclusively the difference in the Finnish Fairway dues charged based on the ships ice class. The fairway dues are charged at the rates shown in Table 3.12 and are applied to the net tonnage of the ship, up to a maximum of 25,000 tons.

Table 3.12: Finnish Fairway Dues [Finnish Transport Safety Agency, 2014]

Ice Class	**Cargo Ship Unit Price/t** (EUR)	**Net FS1A** ($)	**Net PC4** ($)
IA Super (or higher)	0.470	6,506.68	4,155.27
IA	1.098	15,200.71	9,797.42
IB, IC	2.578	35,689.98	22,792.10
II, III	4.381	60,650.56	38,732.42

3.5.5 Maintenance

The maintenance cost reflects the budgeted amount for unexpected damages, specifically related to ice. As mentioned in Section 2.2.2, the budgeted maintenance costs above and beyond expected repairs for ships travelling in ice free waters was around $25,000 USD per voyage. This additional maintenance budget is used for both the NSR and NWP.

3.5.6 Competent Crew

According to the Polar Code vessels operating in water with any ice coverage require ice navigation training. Table 3.13 outlines the cost of basic training versus advanced training (assuming no prior training has been acquired).

Since the port of departure has been chosen as Kokkola, this presents the interesting comparison in that all officers will require ice training in the winter months as it's assumed that Kokkola has ice coverage between the months of November and May. Thus, in the winter months all officers regardless of route taken will require advanced ice training, and in the summer months, the southern route officers will not require any ice training.

For all ice covered water scenarios it is assumed that 2 officers will require advanced training and the remaining officers will require basic training. Obviously, the more available ice training becomes the fewer officers will need the training as they will already have taken the course and this cost will over time decrease to zero cost.

Also included in the crew costs is the cost of an ice pilot for the NSR. The ice pilot is needed for all icebreaker days at a cost of $1,000 per day plus a flat fee of $5,000 for travel and other associated expenses.

Table 3.13: Ice Training Course Costs [Education, 2017]

Course	**Cost (EUR)**
Basic Ice Training	$1,860
Advanced Ice Training	$3,720

Crew's daily pay is also calculated in order to properly capture the daily operational costs for the ships. In the model each crew member is paid $80 per day of transit, and each officer is paid $160 per day of transit [Stopford, 2009]. These values should be changed by the end user to reflect their own crew costs. Daily crew wages are included to account for differences in crew numbers on different ships.

3.5.7 Initial Investment

Initial investment costs in this model are taken to apply exclusively to the difference in cost between a FS1A ice class ship and a PC4 ice class ship. In literature there is a wide range of considered increased initial investments when upgrading the ice class of a vessel. For this project an increase of 30% [Eide and Endresen, 2010] will be used to compare the cost of a PC4 ship over a FS1A ship. In 2014 the new-build cost of the M/V Nunavik was 66.7 million USD [IHS Global Limited, 2017].
The amount of initial investment absorbed by each voyage is the new-build cost of the ship divided over the lifetime of the ship (taken as 7300 days) multiplied by the number of days of transit.

The initial investment costs per day used in this simulation per voyage are shown in Table 3.14.

Table 3.14: Initial Investment Cost per Voyage [IHS Global Limited, 2017]

Ship	Cost (USD)
FS1A	\$6,396
PC4	\$9,137

3.5.8 Capacity, Scheduling and Other Marketing Factors

Without specifying the cargo type and the spot freight rate of that cargo, defining the cash flow of a ship is difficult. However, in order to use this model to compare the feasibility of different ice class ships with different cargo carrying capacities along different routes, there needs to be a defined comparison tool that allows for time averaged or freight averaged total costs to allow for a fair assessment.
In shipping a time charter equivalent (TCE) revenue is traditional defined as a \$/day value that is the freight earnings less the voyage and operational expenses for that voyage, shown in Equation (3.4) [Stopford, 2009].

$$TCE = \frac{FR * C}{t} - VOYEX - OPEX \tag{3.4}$$

Where:
FR = Freight Rate in \$/ton
C = Cargo Carrying Capacity of the ship in t
t = transit time along the route in days
VOYEX = Voyage Expenses in \$/day
OPEX = Operational Expenses in \$/day
CAPEX = Capital expenses in \$/day

The time charter equivalent represents the current voyage earnings in the current shipping market. These earnings can be compared to a ship owner's known capital costs and the ships total revenue is calculated overtime [Stopford, 2009].
Since the freight rate is not defined as part of this project, in order to keep the scenarios general a Recovery Freight Rate (RFR), calculated in Equation (3.5), is defined as the freight rate (\$/ton) that would be required to recover the additional expenses associated with a single voyage. The RFR allows comparison between ships of differing capacities with different schedules or transit times.

$$RFR = \frac{t}{C} * [VOYEX + OPEX + CAPEX] \tag{3.5}$$

Where:
t = transit time along the route
C = Cargo Carrying Capacity of the ship in t,in this model this is taken as the winter deadweight cargo capacity (WDWTCC):
$DWTCC_{winter} = DWT_{winter} - Bunkers - Stores$

WDWTCC for PC4: 30,713t FS1A: 42,477t
VOYEX = Voyage Expenses. Comprised of the fuel costs, insurance premiums, canal tariffs, and port fees. VOYEX is easily calculated by dividing the total voyage costs by the number of days of transit
OPEX = Operational Expenses. Consisting of unexpected maintenance (maintenance due to ice damage) and crew costs (both crew training and daily pay) are also easily calculated in the same manner as the voyage expenses
CAPEX = Capital expenses. In this model, CAPEX only accounts for the initial investment of the ship. The initial investment per day is considered to be the new-build cost of the ship divided over the lifetime of the ship (taken as 7300 days)

3.6 Model Verification

The calculation routines of the speed simulation model in ice for a ship on the northern routes is verified by comparing actual voyage times with the CBM's results.

3.6.1 M/V Nunavik Voyage Comparison

The M/V Nunavik completed a journey through the NWP in 2014. The GPS coordinates of the voyage were posted once a day, usually in the evening (but not always at a consistent time), this allows for the progress of the M/VNunavik to be tracked and the distance travelled each day to be measured, this is shown in Figure 3.7.

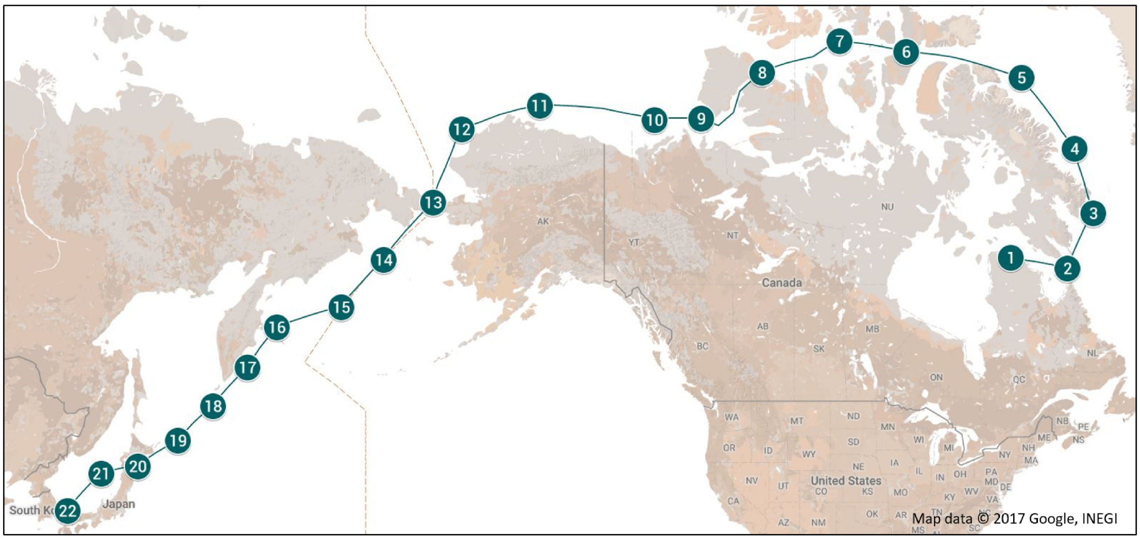

Figure 3.7: M/V Nunavik's Journey through the Northwest Passage Route

The weekly ice data for the September 19 - October 11 journey was collected from the Canadian Ice Service [2016a] and input into the speed model along with the ship parameters for the M/V Nunavik in order to verify the models results. The calculated ship velocity and time of transit for each leg of the journey is shown in Figure 3.8, each leg is considered to be roughly one day according to the log from M/V Nunavik's journey.

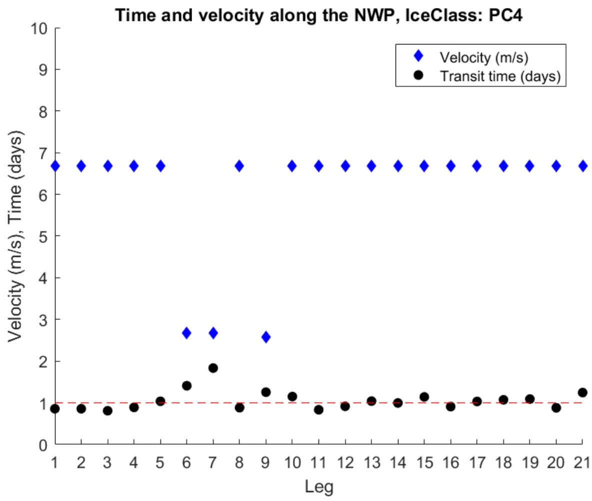

Figure 3.8: Time and Velocity Results for M/V Nunavik's Journey

Legs 1-2 are open water, Legs 3 & 4 are in Baffin Bay, Leg 5 is through Eastern Parry Channel, Leg 6 & 7 are through Western Parry Channel, Leg 8 is through Amundsen, Leg 9 is through the Beaufort Sea and Legs 10-21 are again open water. The red line in Figure 3.8 represents the expected result of one day transit time for each leg. Since the coordinates were not entered at exactly 24hour intervals into the log, the slight variation is an expected result. The maximum speed of the M/V Nunavik is 6.69 m/s.

3.6.2 Distance Table Comparison

Using the simple distance table calculation in Equation (3.6) the time of a voyage at maximum speed in open water can be calculated.

$$VoyageTime = \frac{TotalDistance}{ShipVelocity} \tag{3.6}$$

This simplified calculation assumes no ice coverage and no delays during the entire voyage. This distance table calculation can be used to verify the results of the transit simulations in the summer months, as the ice conditions are at their minimum.

Table 3.15: Comparison between Distance Table Calculation and Simulation Results [Veson, 2017]

Route	**Distance Table**	**Simulation Result**		
		July	**August**	**September**
	(days)	**(days)**	**(days)**	**(days)**
NSR	24.9	24.9	24.9	25.4
SCR	35.8	35.8	35.8	35.8
NWP	24.1	26.2	24.4	24.1
PCR	29.9	29.9	29.9	29.9

As can be seen in Table 3.15, when ignoring the transit delays through the canals, the transit times for the PCR and SCR are identical to the distance table calculations. The northern routes still have ice coverage even in the summertime, more on the NWP than the NSR, thus the transit times are slightly longer for these routes.

Chapter 4

Results

This thesis project presents the development of a Cost-Benefit Model designed as a tool to determine economic feasibility of shipping through the Arctic. The model results are both characterized and limited by the inputs entered. In Chapter 3 the model parameters and inputs are presented for a simulation designed to explore two extreme cases within the model. These cases are then compared and contrasted to investigate the general benefits of using a higher ice class ship versus a lower ice class for shipping bulk cargo through the Arctic with consideration given to fulfilling the requirements outlined in the Polar Code.

The CBM takes into account seven decision factors, which are used to create the desired scenario. These factors are as follows:

1. Month of Transit:. This dictates the ice data input used for the ship velocity in ice calculation on the northern routes.

2. Ice Class of Ship In this thesis project only ice classes PC4 and FS1A are explored.

3. Loading Condition: Can be set to either Laden or Ballast. This directly affects the value of the canal tariffs on the SCR and PCR. This parameter also effects the weight of the ship and thus the speed and fuel consumption. In this project, the ships are considered to always be fully laden.

4. Fuel Type: Is either warm fuel, all ships operate using IFO or cold fuel, all northern route ships use NDF and southern route ships use IFO.

5. Mandatory Icebreakers: This variable controls the operational limitations (or speed) of the ship. It icebreakers are mandatory, the ship is assumed to be escorted at all times, if icebreakers are unavailable the ship is assumed to never be escorted, and if icebreakers are not mandatory, the ship will assume to operate independently until an icebreaker escort is required to proceed according to POLARIS.

6. Piracy Levels: Directly effects the additional insurance for armed guards on the Suez Canal route. There are three options: High, Medium or Low risk.

7. Canal Negotiations: Accounts for the ability to negotiate NSR tariffs, if this is set to Yes than the NSR tariffs are taken to be equal to the SCR canal tolls. Ice pilot and other ice related costs are not affected by this variable.

If the simulation is run for both ice classes simultaneously there are over 500 possible scenarios generated from the CBM. Each case depends on the users choice of decision factors and model inputs focused on a particular scenario of interest to the user (perhaps a ship owner).

4.1 Transit Times

On the northern routes, the transit time of the ships varies relative to the ice conditions. On the southern routes, canal queueing delays are the only variable effecting transit time, as the ships are assumed to be able to operate at a constant speed in open water at all times. Figure 4.1 shows how the transit times for the different ice classes varies for time of year and icebreaker usage on the northern routes.
Figure 4.1 show the number of total transit days for both the NSR and the NWP, the solid blue (PC4) and green (FS1A) lines. The total transit days include days spent in ice and in open water. The dashed lines represent the number of transit days an icebreaker is required on that route by that ship. Days that an icebreaker is required are set by the POLARIS operational limitations. For example, since the blue dashed line is always at zero days, the PC4 ship is able (and assumed) to operate year round as an independent vessel in this simulation.

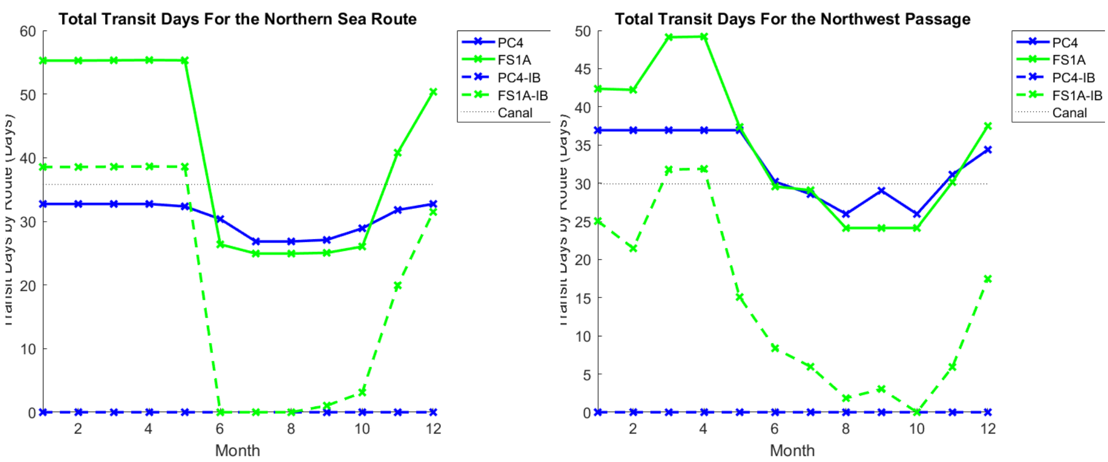

Figure 4.1: Total Transit and Icebreaker Days for the NSR and NWP

As seen in Figure 4.1 the PC4 ship never requires the use of an icebreaker. According to POLARIS's operational limitations the PC4 ship will always be able to proceed independently in the NSR and NWP. This is an advantage, as there would be no delays due to waiting for icebreaker support, provided no emergency situations arise.

The FS1A ship can independently transit the NSR from June to August, but transit of the NWP can only be done independently in October. Noting that these results are only valid for the given ice conditions (See Appendix A). With global warming creating more favorable ice conditions (from a shipping perspective) the FS1A ship may in the future be able to transit the Arctic seaways independently for larger portions of the year.

The black line in Figure 4.1 represents the average time taken to transit the SCR or PCR. As it can be seen on the NSR a PC4 ship will always have a shorter transit time than on the SCR. The FS1A ship will only have shorter transit time in the summer months between June and October. On the NWP both ships only have shorter transit times in the summer months between June and October. This is due to more severe ice conditions on the NWP compared to the NSR.

It should be noted that a PC4 ship experiences less variance in the time taken to transit the northern routes, with only a small deviation over the course of the year. The FS1A ship experiences a much larger range of transit times. Table 4.1 shows the maximum and minimum transit days for each ship according to route.

Table 4.1: Maximum and Minimum Transit Times

Route	**Ice Class**	**Max. Days**	**Min. Days**	**Difference**
NSR	PC4	32	27	5
NSR	FS1A	64	25	39
NWP	PC4	30	26	4
NWP	FS1A	51	24	27

4.2 The Case Studies

For the purpose of this thesis project, the model results are presented for: a worst case scenario, or the largest difference in costs between the north and south routes, and a best case or lowest cost differential case study. These case studies are representative of the outside parameters of the model results. The results are obtained with the inputs outlined in Chapter 3 and the decision factors described below.

Discussion around the results of these two models includes evaluation of the impact of individual factors and how they compare to each other for each route and ice class. Contrasts between the PC4 and FS1A vessel are also discussed as well as their differing performance on each route.

4.2.1 The High Differential Case Study

The highest case study is representative of the largest difference between the cost of the North and South routes. It is characterized by high tariffs on the NSR, mandatory use of naval distillate fuel in northern climates and low piracy rates around the Suez Canal. The winter months are featured as this is when the worst ice conditions are present along the northern routes, slowing vessels transit times and increasing their need for icebreaker escort.

In this scenario icebreakers escort is dictated by the POLARIS operational limitatinos, in order to compare the number of icebreaker days required for the two different ice classed ships. This may not be realistic on the NSR as ships are usually required to have an icebreaker escort depending on their ice class and the ice conditions. In the winter months, for typical ice conditions, an icebreaker escort would most likely be mandatory for both a PC4 and FS1A ship. The NWP does not have a mandatory requirement on the use of icebreakers. In reality, an icebreaker escort is very unlikely in the NWP.

Most ships choose not to travel the Arctic seaways in the winter months because of the more severe ice conditions and weather. This scenario helps examine a case study that is more likely to be realized in the future as polar ice continues to melt reducing some of the risks or Arctic transits. The use of NDF on the northern routes allows for a comparison of the effects of bunker prices on voyage costs. And the high tariffs on the NSR reflect the current official NSR tariffs according to the NSRA.

4.2.2 The Low Differential Case Study

The lowest case study is representative of the closest gap between the cost of the north and south routes. It is characterized by negotiated NSR tariffs, use of "warm" or IFO fuel on all routes and high piracy occurrence around the Suez Canal. The summer months are featured as low ice coverage speeds passage through the northern routes and gives the lowest northern transit times. Icebreaker escorts are again dictated by POLARIS.

The low case study is a close representative of the shipping market in 2011-2013 when the NSR saw a marked increase in shipping traffic, with the exception of nonmandatory ice breaker escorts on the NSR. This implies that on the NSR the transit tariffs would likely be higher than they are presented in this simulation, especially for the PC4 ship which currently has no requirement for an icebreaker escort. In 2011-2013 piracy around the Suez canal was a serious risk, with the additional insurance premiums for armed guards being very high. The non-Russian flag ships transiting the NSR all did so in the summer months and the NSR transit tariffs were being negotiated to much lower than the official NSRA tariffs.

4.3 Total Costs of Single Voyage

The total costs of a single voyage are calculated by summing the total transit costs for additional insurance, unexpected maintenance, competent crew costs, initial investment, port fees, fuel costs and canal tolls or transit tariffs.

4.3.1 The High Differential Case Study

In Figure 4.2 the total costs for the high case study are presented. The downwards pointing black triangles represent the total number of days for the transit and the upwards point ones represent the number of those days that the ship required icebreaker assistance according to the POLARIS operational limitations.

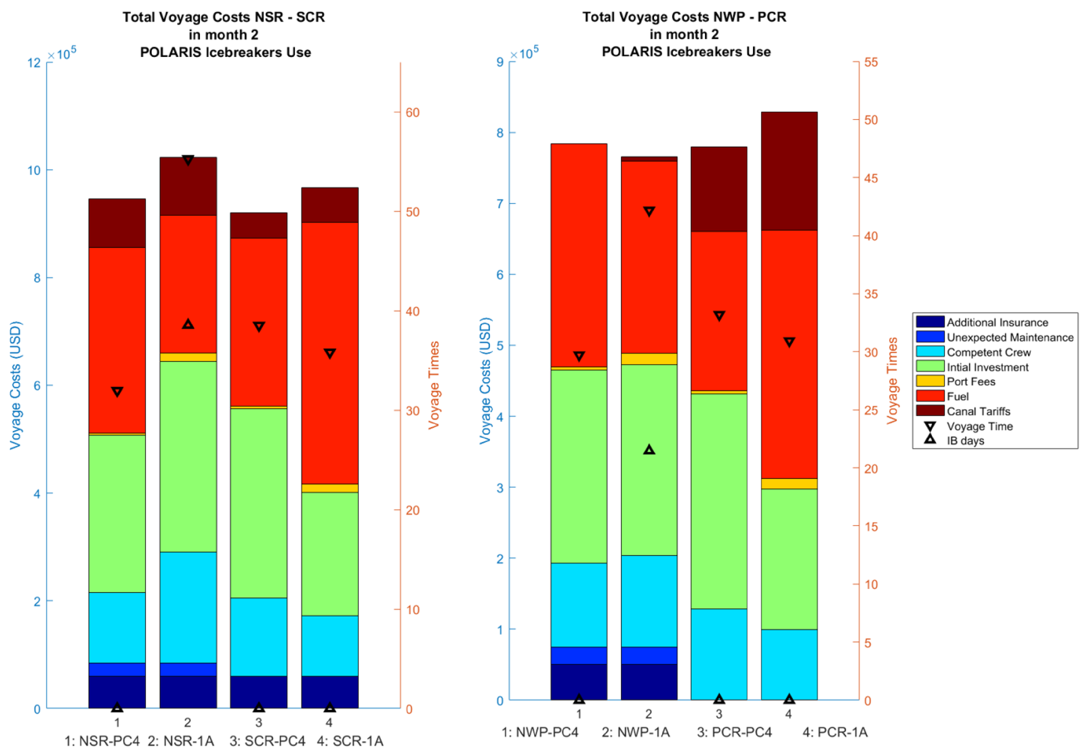

Figure 4.2: Total Costs and Transit Days for High Case

As seen in Figure 4.2, the two largest contributors to the total cost of a single voyage are the fuel costs followed by the initial investment. Fuel costs are directly effected by two factors: fuel consumption of the ship, and bunker prices.

Fuel consumption on the northern routes is directly effected by the severity of the ice regime the ship encounters. On both the NSR and NWP the PC4 ship is not required by the POLARIS operational limitations to have an icebreaker escort, while the FS1A ship requires an icebreaker escort almost the entire time it is in ice-covered waters. The ice regime the FS1A ship encounters behind an icebreaker is less severe than what the PC4 ship encounters. This leads to larger fuel consumption costs for the PC4 ship. However, because of the operational limitations placed on the FS1A ship in the winter ice conditions it's transit times are much longer then the PC4 ship, with an additional 24 days required on the NSR and 13 days on the NWP.

On the southern routes, it can be seen that fuel costs for the PC4 ship are smaller than for the FS1A ship, despite having a longer transit time. This is due to the newer, more efficient machinery on board the M/V Nunavik and the wider breadth of the M/V Nordic Barents. The specific fuel oil capacity of the M/V Nunavik is more efficient than that on the M/S Nordic, thus the PC4 ship needs less fuel for the same distance covered. The other factor is the wider breadth and blunt bow of the M/V Nordic Barents as this is one of the main factors contributing to the higher open water resistance for the FS1A ship. The longer southern route transit time for the PC4 ship is due to it's 0.5 knot slower open water service speed.

The bunker price of fuel does effect the fuel costs of a voyage. For example, the PC4 ship on the NSR spends a total of $66,640 more on fuel in the high case scenario when using NDF compared to IFO, that's a 7% increase in total voyage costs.

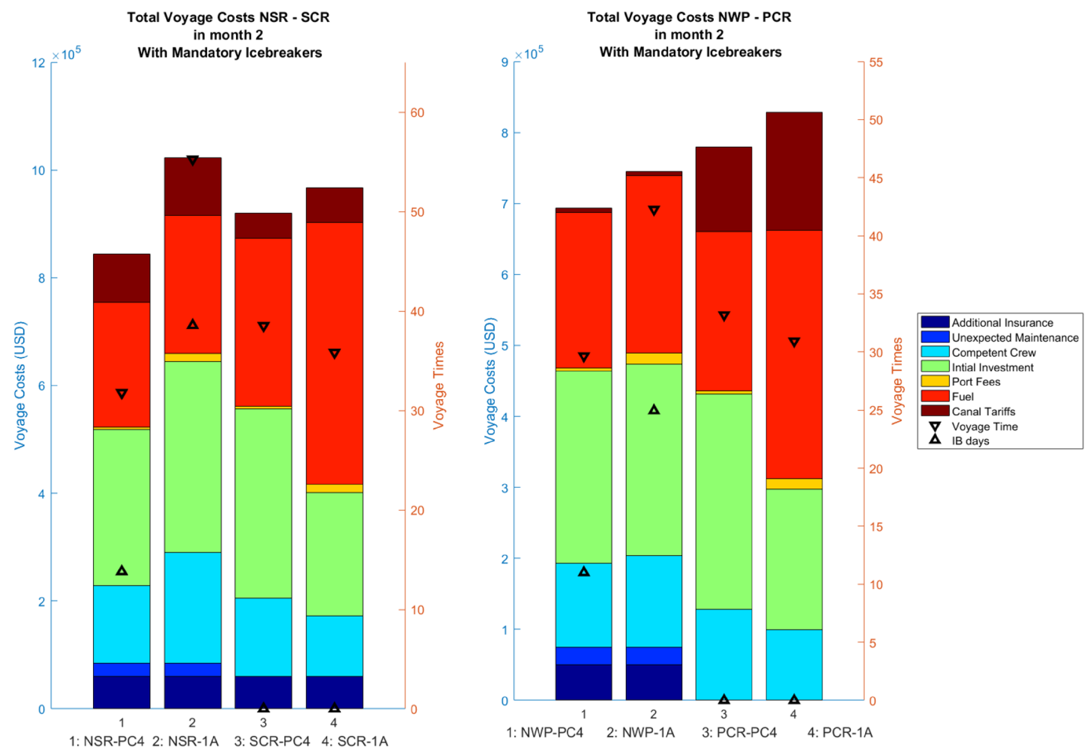

Figure 4.3: Total Costs and Transit Days for High Case with Mandatory Icebreaker Escort

The number of days a ship is escorted by an icebreaker also makes a large difference in the fuel consumption. Figure 4.3 and Figure 4.4 show the same transit simulation except that in Figure 4.3 it is mandatory for ships to have be escorted by an icebreaker for legs 2-8 of their routes, whereas icebreakers are completely unavailable for escort operations in Figure 4.4.

When icebreaker escorts are mandatory in ice covered waters, using the PC4 ship on the northern routes becomes feasible as it has both the lowest transit times and the lowest total single voyage costs. The simulation results change very little with mandatory icebreaker escorts for the FS1A ship as under the POLARIS operational limitations it already required an icebreaker escort for most of it's voyage.

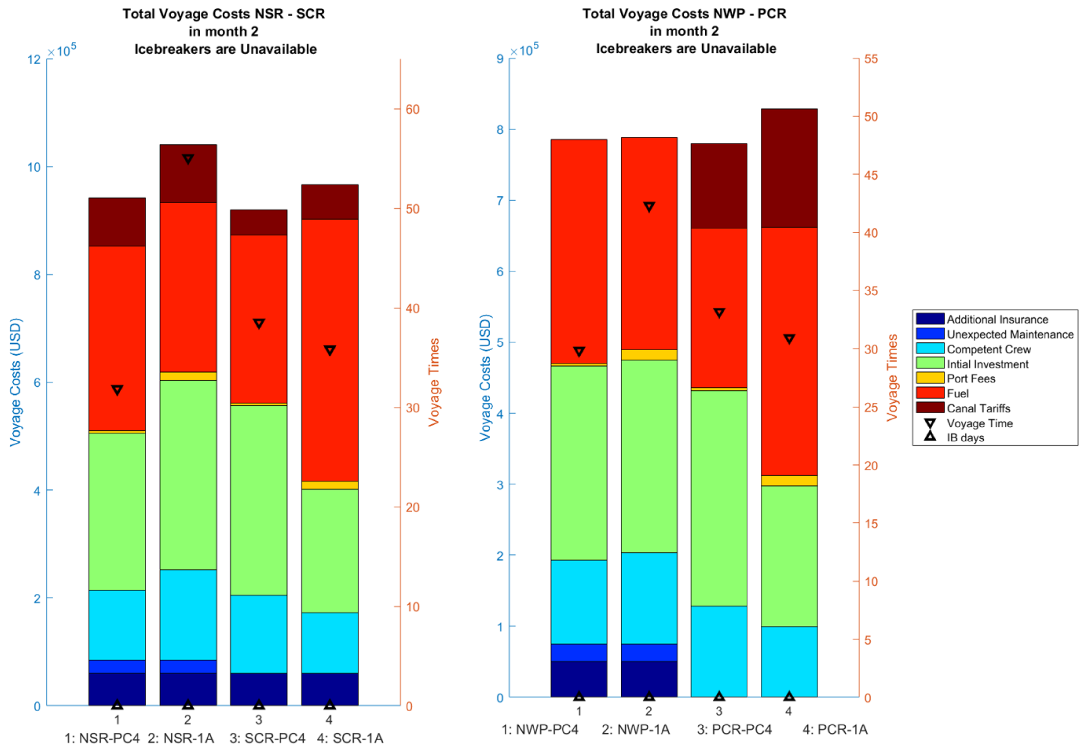

Figure 4.4: Total Costs and Transit Days for High Case with No Icebreaker Escort

On the NWP, icebreaker escorts are not mandated by the Canadian government and according to companies interviewed escort is unlikely, unless a private icebreaker is hired for the voyage. This would add an additional cost to the voyage (not included in this project) likely making the trip less economically feasible. If icebreakers are unavailable on the NWP the FS1A ship is an economically feasible option when looking at the total single voyage costs, however it should be noted that the reason for the very long transit time is that the ship is often stuck or only able to proceed at very slow speeds in the severe ice conditions. The PC4 vessel is only \$16,000 more expensive on the NSR compared to the SCR, with a shorter transit time by 7 days. The PC4 vessel is also able to proceed independently along the northern routes according to the POLARIS operational limitations, making it a safer option than the FS1A ship.

4.3.2 The Low Differential Case Study

In Figure 4.5 the total costs for the low case study are presented. In this scenario, the southern routes are more expensive than the northern routes, with consistently longer transit times. The ice coverage in the summer months is very low for both the NSR and NWP, consequently icebreaker use is confined to only 4 days for the FS1A ship on the NWP.

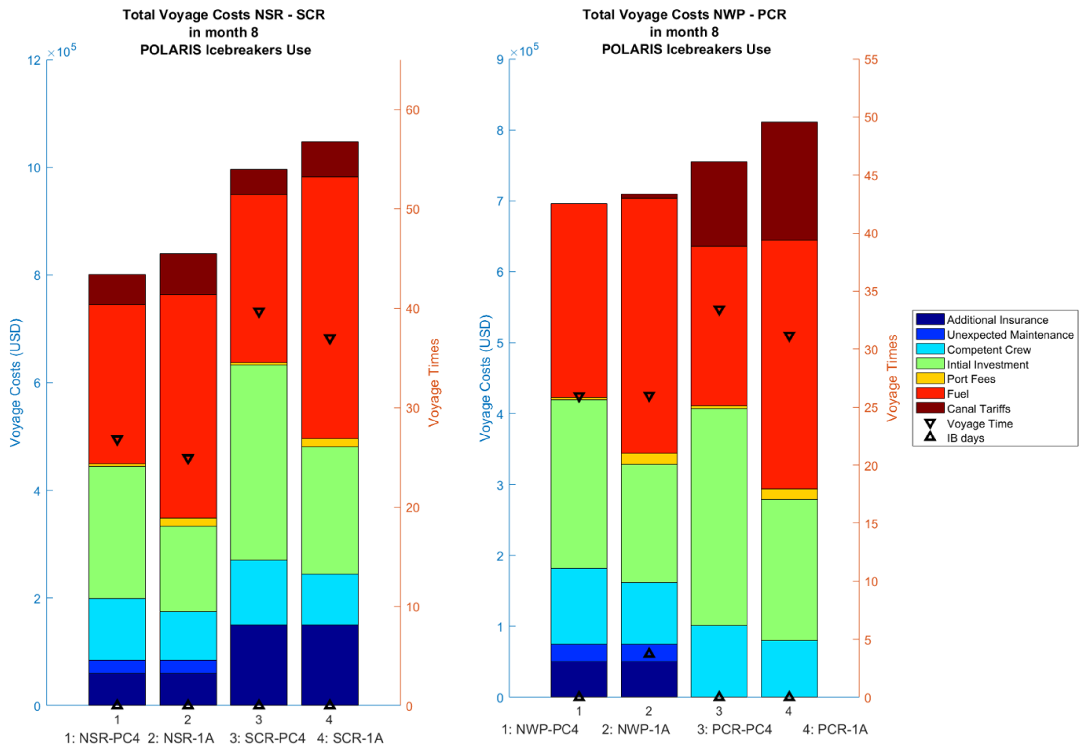

Figure 4.5: Total Costs and Transit Days for Low Case

Again in this case study the fuel costs are the largest contributor to the total single voyage cost, followed by the initial investment. The initial investment costs are directly tied to the number of transit days, with a fixed capital cost assigned to each day. The longer the voyage, the more capital cost assigned to that single voyage. In reality, this is not how shipping accountants usually account for the capital cost of a ship in their books, instead deducting ship depreciation on the annual cash flow statements spreading the initial investment cost of a new ship over the lifetime of the ship [Stopford, 2009].

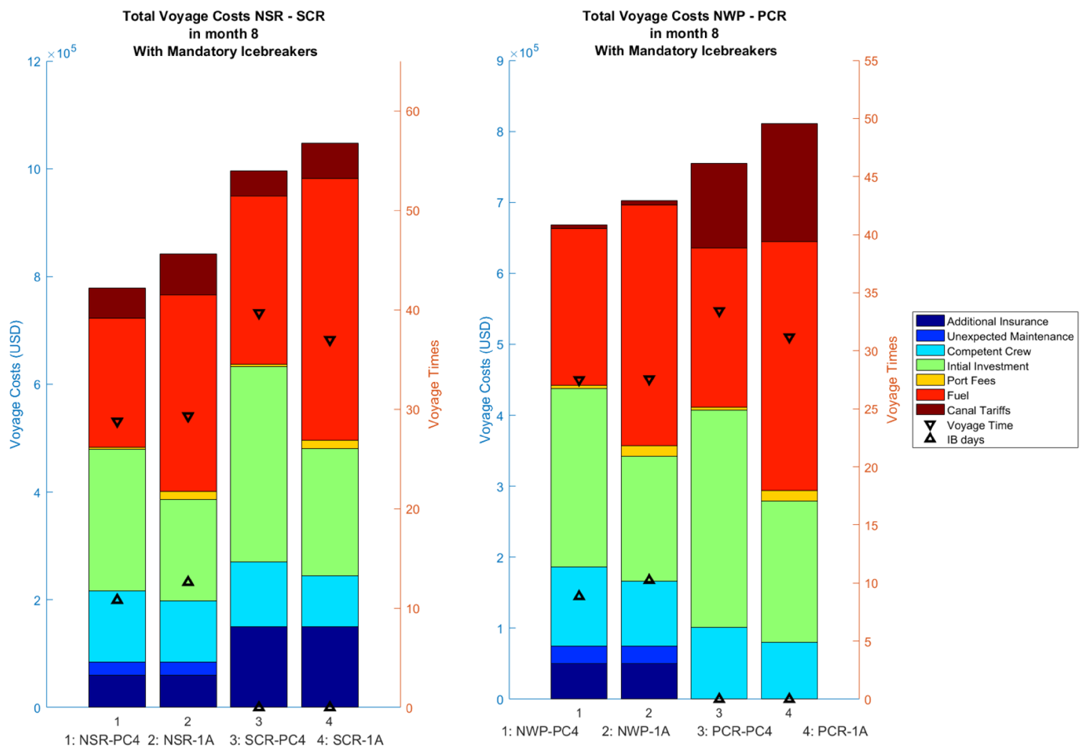

Figure 4.6: Total Costs and Transit Days for Low Case with Mandatory Icebreaker Escort

Figure 4.6 shows the total costs of a single voyage, if icebreaker escort is mandatory. Unlike in the high case study, mandatory icebreaker assistance has almost no effect on the transit times of the northern routes. The largest difference is seen in the fuel consumption of the northern ships. Table 4.2 shows the cost of fuel per single voyage saved by each ship on each route.

Table 4.2: Fuel Savings with Mandatory Icebreaker Escort

NSR-PC4	**NSR-FS1A**	**NWP-PC4**	**NWP-FS1A**
$55,019	$45,578	$57,285	$20,272

Figure 4.7 shows the total single voyage costs with no icebreaker assistance. Both ships remain faster and cheaper on the northern routes compared to the southern routes, with a slight increase in total voyage costs for the FS1A ship.

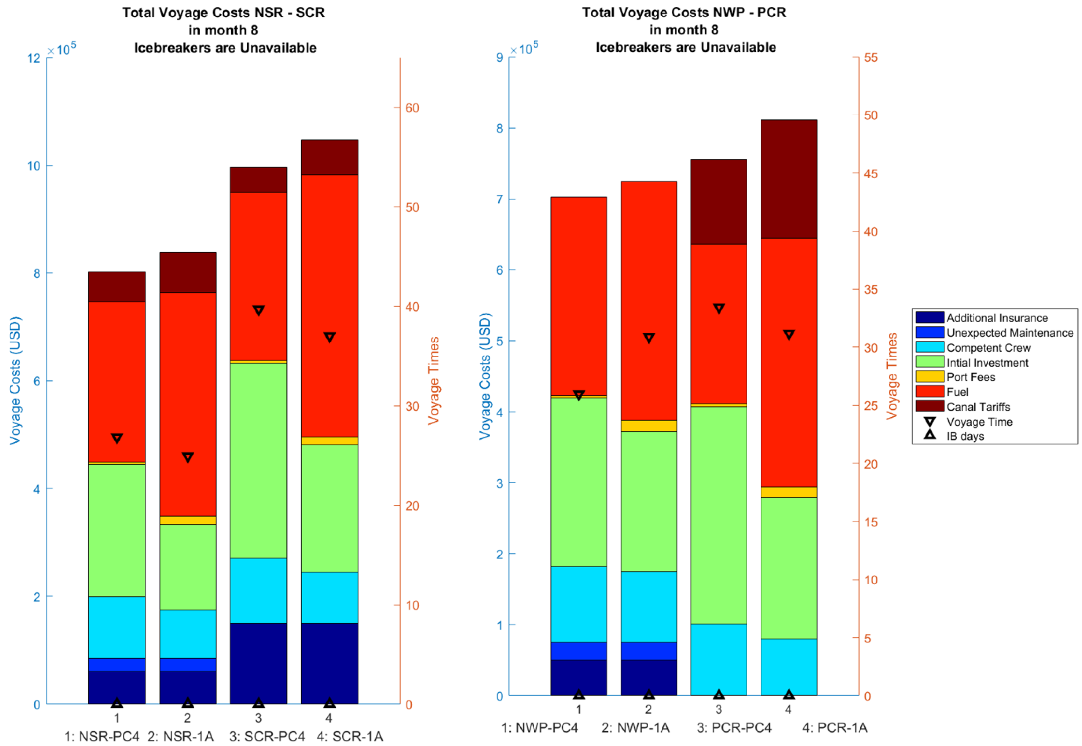

Figure 4.7: Total Costs and Transit Days for Low Case with No Icebreaker Escort

4.4 Voyage, Operational & Capital Expenses

Daily expenses or time charter averaged costs are defined for this model as the voyage, operational and capital costs of a voyage divided by the number of days of transit. Table 4.3 and Table 4.4 show the total expenses for the high and low case studies for each route and ice class, with number of days with an icebreaker escort dictated by POLARIS.

By looking at the expenses instead of the total single voyage cost, the effect of transit time is captured. For example in the high case, Table 4.3, it can be seen that the total expenses of the FS1A ship are lowest on the northern routes. However in the low case, Table 4.4, the FS1A ships total expenses are the highest on the northern routes. In the high case the FS1A has significantly longer transit times on the northern routes compared to the low case where it has the shortest transit times, thus the difference in total expenses.

Table 4.3: High Case Daily Expenses

	Units	NSR		SCR	
		PC4	FS1A	PC4	FS1A
Voyage Expenses	$/day	15,563	7,953	10,972	17,476
Operational Expenses	$/day	4,870	4,171	3,764	3,131
Capital Expenses	$/day	9,137	6,396	9,137	6,396
Total Expenses	$/day	29,570	18,519	23,874	27,003
	Units	NWP		PCR	
		PC4	FS1A	PC4	FS1A
Voyage Expenses	$/day	12,401	8,053	10,468	17,175
Operational Expenses	$/day	4,826	3,637	3,881	3,222
Capital Expenses	$/day	9,137	6,396	9,137	6,396
Total Expenses	$/day	26,364	18,086	23,486	26,793

The capital expenses are constant for all routes, in both case studies, because they only reflect the difference in construction costs, divided per days of ship service, for the more expensive PC4 ship versus the lower ice class FS1A ship.

The operational expenses in both case studies however are always more for the PC4 ship. This is due to the higher crew costs for the ship as there are more officers on board (at a higher daily wage). The reason for more officers on board is likely due to the design intent behind the M/V Nunavik. It was designed to operate year round in the NWP, thus the number of officers reflect the ship operators desire to have an ice navigator(s) and/or pilot on board at all times. The operational costs are also consistently higher for the northern routes compared to the southern routes, and this is due to two factors. First, the southern route ships have a summer month exemption from requiring crew to have ice navigation training. And second the shorter transit times on the northern routes give less days for the unexpected ice damage maintenance cost to be distributed across.

Table 4.4: Low Case Daily Expenses

	Units	NSR		SCR	
		PC4	FS1A	PC4	FS1A
Voyage Expenses	$/day	15,448	22,515	12,918	19,358
Operational Expenses	$/day	5,198	4,584	3,040	2,560
Capital Expenses	$/day	9,137	6,396	9,137	6,396
Total Expenses	$/day	29,783	33,495	25,095	28,314
	Units	NWP		PCR	
		PC4	FS1A	PC4	FS1A
Voyage Expenses	$/day	12,794	16,530	10,407	17,069
Operational Expenses	$/day	5,078	4,308	3,040	2,560
Capital Expenses	$/day	9,137	6,396	9,137	6,396
Total Expenses	$/day	27,009	27,233	22,584	26,025

The voyage expenses are more complex to contrast and compare. From the total single voyage costs it was shown the largest contributor to the total cost was the fuel consumption costs and this factor is effected by transit time, ice regime and icebreaker assistance.

In the high case, the PC4 ship operates on both northern routes without icebreaker assistance and thus encounters a larger in ice resistance, thus consuming more fuel. It also has a shorter transit time comparison to the FS1A ship. All of these factors ensure that the voyage costs of the PC4 ship are much higher than the FS1A ship on the northern routes. However, in the low case study the PC4 ship has lower fuel consumption because the ice conditions in the summer are less severe. Thus, in the low case the PC4 ship has the lower voyage expenses. The insurance premiums, port fees and canal tolls collectively contribute only 15-21% of the total voyage expenses on the NWP and 27-42% on the NSR, making them less important in the analysis. On the southern routes, however the fuel costs remain fairly static for each ship with the FS1A ship always having the higher voyage expenses. This is because the canal tolls for the SCR and PCR are greater for the FS1A ship as it has a higher cargo carrying capacity, than the PC4 ship by 4,460t. The fuel costs, as discussed in Section 4.3, are also higher for the FS1A ship. Port fees, or Finnish Fairway dues are again higher for the FS1A ship. Insurance premiums on the southern routes are limited to armed guards, only applying to the SCR and are equal in cost for both vessels.

When looking at the total expenses compared to the total single voyage costs in the low case study, it should be noted that they produce reverse results for economic feasibility of the northern routes. In the low case (see Table 4.4) the northern routes have consistently higher expenses, however the northern total single voyage costs (see Figure 4.5) are lower than the southern routes. The difference in these results are due to the much shorter transit times, by 6-13 days, on the northern routes in the summer. The shorter the transit time the less days fixed costs, like maintenance, insurance or canal tolls, are divided across which means higher expenses. However, shorter transit times also allow a ship operator to increase their load-factor potential for that ship, provided they can find consecutive work for the ship. If freight rates are high, shorter transit times become preferable. Whereas in a low market, slow steaming or longer transit times are preferred by ship owners.

4.5 Recovery Freight Rate

Recall that the Recovery Freight Rate is defined as the freight rate ($/ton) that would be required to recover the voyage, operational and capital expenses associated with a single voyage as defined in this CBM, see Equation (3.5). Table 4.5 shows the RFR's for all routes and ice classes for both the high and low case.

Table 4.5: Recovery Freight Rates as Calculated by the Cost-Benefit Model

Season & Icebreaker Availability	**Units**	**PC4**	**FS1A**	**PC4**	**FS1A**
		NSR		**SCR**	
Winter POLARIS	$/ton	32.88	25.20	32.12	23.82
Winter Mandatory	$/ton	29.45	25.20	32.12	23.82
Winter None	$/ton	32.83	25.47	32.12	23.82
Summer POLARIS	$/ton	28.00	20.52	34.79	25.79
Summer Mandatory	$/ton	27.20	20.72	34.79	25.79
Summer None	$/ton	27.89	20.59	34.79	25.79
		NWP		**PCR**	
Winter POLARIS	$/ton	27.32	18.96	27.22	20.41
Winter Mandatory	$/ton	24.19	18.34	27.22	20.41
Winter None	$/ton	27.41	19.48	27.22	20.41
Summer POLARIS	$/ton	24.41	17.51	26.38	19.98
Summer Mandatory	$/ton	23.36	17.29	26.38	19.98
Summer None	$/ton	24.51	17.87	26.38	19.98

The RFR's give another way to compare the different ice classes as they account for both transit time and cargo carrying capacity. However, the RFR's are only valid within this model and cannot be used to compare to true freight rates, as the RFR represents the margin between operation in polar waters and normal operation. Factors such as P&I insurance, ship maintenance other than from ice damage and other operational overhead costs are not included in the models calculated costs, thus the RFR's seen here will be lower than the actual freight rate required to cover the expenses as calculated by a shipping company.

When comparing the different ice classes, with or without icebreaker escorts, the RFR's for the FS1A ship are consistently lower than that of the PC4 ship, making it the most economical ship. This is due primarily to the larger cargo carrying capacity of the FS1A ship.

As seen in Table 4.5 in the summer months (represented with the low differential case study) the northern routes, regardless of ice class or icebreaker availability, are more economical than their corresponding southern routes. This is due to the decreased time of transit and consequent fuel savings, which are possible because of the less sever ice conditions in the summer months.

In the high differential case study the results are not as straight forward. For example, the PC4 ship is not an economical option compared to the southern routes, unless an icebreaker escort is mandatory for all ice covered waters. However, the PC4 ship is still not economical on the northern or southern routes compared to the FS1A ship. In the winter, taking the FS1A ship on the NSR is not a feasible option, even if icebreaker support is available for the whole transit. However, the FS1A ship on the NWP is a feasible alternative, with or without an icebreaker. This is due in large part to the long transit times required by the FS1A ship to transit the NWP. As discussed previously, even if the FS1A ship is economically feasible when viewed from the RFR perspective, it's long transit times are due to strict operational limitations. In the CBM, ships are taken to always be able to transit (at very low speeds), even if POLARIS dictates that their operation is still highly inadvisable with an icebreaker escort. Thus in the CBM, the long transit times for the FS1A ship also indicate a more risky voyage.

Chapter 5

Discussion

This section summarizes the impacts of the Polar Code on Arctic shipping, broadly discusses the results of the research simulation, compares theses results with several previous cost-benefit studies and discusses possible future uses of the Cost-Benefit Model.

5.1 Polar Code Compliance

On January 1, 2017 the Polar Code came into force as a mandatory amendment to SOLAS and MARPOL regulations. The Polar Code contains several important points that have a direct impact on a feasibility assessment of shipping through the Arctic Seaways. These include:

- Polar Certificate: All vessels transiting through ice-covered waters will need to obtain a Polar Certificate. The difficulty and cost of obtaining this certificate is yet to be determined in the shipping industry.
- PWOM:Vessels wishing to transit through polar waters will need to prepare a polar water operating manual for each voyage. This PWOM requires emergency evacuation and environmental emergency responses to be outlined as well as a route planning to determine the operational limitations that the vessel may face on it's journey.
- Ice Training for Crew: This requirement makes operation in ice-covered waters training mandatory for officers in charge of a watch. This training is an additional cost and time off-ship that crew new to Arctic shipping will incur on their maiden Arctic voyage.
- Ship construction: Split into two categories, strength & power and environmental, ship construction has the potential to be a costly consequence of shipping in the Arctic. Before obtaining a Polar Certificate a ship inspection must be performed to ensure that it does meet requirements such as adequate hull strength to withstand ice pressure, sufficient power to overcome ice resistance, and adequate waste storage & processing facilities to meet MARPOL

waste discharge in the Arctic requirements. When purchasing a new ship designated for Arctic shipping the increased cost of construction for higher ice class ships must be considered. As well as the cost of adequate navigation, communication and deicing equipment. While not addressed in the Polar Code as adopted, invasive species control, minimizing marine noise from machinery and reduced carbon emissions are also factors that in the future ship owners may have to address under a revised Polar Code.

5.2 Economic Cost-Benefit Model

The CBM was run for two case studies, a high differential case study representing the largest gap between the northern and southern route voyage costs, and the low differential case study, representing the smallest gap. From these two case studies there are a total of 16 results accounting for 4 different routes, 2 different ice class ships and 2 seasons. These results can be run with varying levels of icebreaker support available. Several conclusions are drawn by comparing and contrasting these results.

Fuel costs are the largest single factor effecting overall voyage costs. They are influenced by the bunker price or type of fuel used and the amount of fuel needed to complete a voyage. The lower the ship's resistance, the more efficient the machinery on the vessel, the slower the vessel, or the more effectively a ship breaks ice, the less fuel is used on a voyage. In this project the PC4 vessel had a lower resistance, more efficient machinery (newer ship), and slower speed than the FS1A vessel, usually resulting in lower fuel costs for the same voyage lengths in open water. Ice breaking ability also effects the ships speed and overall transit time.

The availability of icebreaker assistance in the winter months is another important factor to consider when evaluating the use of the northern routes. Ships transiting behind an icebreaker experience less resistance in ice and consequently require less fuel. The PC4 ship never needs an icebreaker escort according to the operational limitations set by POLARIS, thus it's fuel costs closely mirror the severity of the ice regime encountered. The FS1A ship requires icebreaker escorts for most of the year, and while this eases the ice resistance and fuel consumption, the total transit time is increased as the ship is usually operating with speed limitations. Should icebreaker escorts be mandatory, as is often the case on the NSR, the PC4 ship benefits the most with increased transit times and lower fuel consumption. If icebreaker support is not available the FS1A ship will not be able to operate safely within the POLARIS operational limitations for 7 or more months of the year.

Market conditions largely effect the interpretations of the cost and expense results from the models. In a high freight rate shipping market shorter transit times are much more beneficial as the ship will be working more days because the demand for ships is high. Thus ship operators may be willing to make less profit per voyage by shipping through the Arctic seaways because of their ability to increase the ships load factor. The PC4 vessel has shorter transit times through the Arctic seaways (and compared to the southern routes) and thus in a high market these vessels become more cost-beneficial, especially in the summer months. However, in a low market the advantage of shorter transit times disappears. In a low market the RFR of a northern route needs to be lower then that of the southern routes as it is in the low case study, otherwise the northern routes are not a feasible option from either a time-saved or a profit made perspective. The FS1A ship is the more economically feasible ice class for a low market. However, it's very long transit times in the winter months, make it only a seasonally feasible option to use on the northern routes.

5.3 Comparison to Previous Studies

There have been many previous cost-benefit analysis done for the Arctic routes, all exploring different factors with widely varying inputs. The results of these studies are not consistently positive or negative about the feasibility of the Arctic seaways, and depending on the scenario and variables each study considers, different results are obtained.

In their discussion about their construction of a decision-support model for liner transport through the NSR, Erikstad and Ehlers [2012] concluded that the optimal ice class for liner vessel trading on the NSR was an FS1A ice class. Looking at the RFR's from the CBM, the FS1A is the more economically feasible ship, in the summer and winter. However it also has the longest winter transit times and is restricted by POLARIS to require icebreaker escort for most of the year. Erikstad and Ehlers's model is based on decreasing trends in ice coverage and increasing bunker prices. However, when looking at these trends, they fail to consider the construction of the ship for open water efficiency versus icebreaking efficiency, as well as an individual ships power requirements in either operation. They postulate that slow-steaming could be used along the NSR, with the ability to speed up sailing time if necessary. This would only be possible under the Polar Code, if the ship's increased speed was not operationally limited. Which is the case in the winter months for the FS1A ship, but not the PC4 ship.

Lasserre's [2015] simulation for liner trade concluded that winter operations were not feasible on either the NSR with a FS1A ship or on the NWP with a PC4 ship. Looking at the CBM's RFR results, a PC4 bulk carrier was also found to be non-economically feasible on the NSR or NWP. However, like Lasserre's simulation the difference in RFR (Lasserre uses cost per TEU) is very slight, +0.4% cheaper for the NWP in Lasserre's simulation and -0.7% in the CBM's results. Lasserre's conclusion that the speed of transit was a crucial determinant in the economic feasibility is consistent with the CBM's results. Lasserre's remarks about the importance of load factor and market conditions in feasibility estimates was also heavily supported by the CBM.

Kujala et al.'s paper determined that POLARIS is a reliable tool to assess the encountered risks due to ice and operational limitations of ships in ice. With the Polar Code calling for ships to provide a detailed risk assessment and plan for risk mitigation on their intended route, the use a CBM with a risk assessment tool is essential to appropriately estimating ships speed and transit times in ice-covered waters. The CBM's ability to calculated the ships velocity in different ice types improves the estimating accuracy according to Riska and Valkonen [2014]. This is important because fuel costs account for the largest portion of voyage costs leaving the model's results sensitive to the accuracy of the calculated ship speed and time of transit, which are directly effected by POLARIS operational limitations, as seen in the total single voyage cost results for scenarios with and without an icebreaker.

5.4 Future Model Use

There are several ways that the Cost-Benefit Model can be used by an end user. The CBM could be used to estimate transit speeds and voyage costs for a single voyage in order to make a last minute decision on whether or not to use the northern route over the southern route. Using real time egg code ice data for each leg of their planned voyage. Ideally each leg would be comprised of a single consistent ice regime. The ice parameters, like ice flexural strength etc, could also be updated to reflect the current region and ice season. The end user could also use the CBM, with the monthly averaged ice data presented in this project, to plan north or south route usage for a yearly time charter. In both of these situations, the voyage, operational and capital cost parameters like, the insurance premiums for ice damage or armed guards that the ship company has been offered, the current cost of bunker fuel, and the current freight rate, could all be entered into the model to give a current snapshot of the cost comparison for the voyage or time charter under consideration.

The CBM is only as accurate as the model inputs and there are two categories of parameters that can be adjusted in the CBM to allow a future user to tailor the model to their shipping scenario and output interests. First is updates to the ship-ice simulation that translates to ship speed in ice and transit time within the CBM. The ship-ice simulation relies heavily on the accuracy of the ice data inputted to the model. The more accurate the ice data and the more consistent an ice regime within each leg is, the more accurate the ship-ice model. Second, is adjustments to the operation, voyage and capital parameters. The current values used in the model are meant to be as accurate an average representation as possible; however, there are several variable or factors that could be added to or explored in more depth within the model to more accurately capture the complexities of the feasibility calculation of the Arctic seaways. These factors include:

- The current initial investment calculation does not include ship depreciation, assuming that every day that the vessel sails a fixed, equal portion of the new build ship price is added to that voyages capital costs. Depending on the ship and payment/accounting scheme this calculation could be updated.

- In this simulation the only port fees considered are for the Finnish fairway dues because these are directly affected by the ships ice class. In reality the port fees in Vancouver, Shanghai and Kokkola would be slightly different for different vessels, depending on the method of calculation of port fees. However, as it can be seen just by including the Finnish fairway dues, port fees are not a significantly large portion of the overall costs and thus this addition would likely not effect the overall results by any significant measure.

- Canal tolls and the NSR tariffs are commonly known to be negotiable rates, although the level of negotiation varies. An end user using the model can easily enter their own values for tolls and tariffs based on their previous experience. The same is true of insurance costs.

- Maintenance costs currently only reflect maintenance for unexpected damages due to ice. Regular maintenance, dry-dock fees, classification surveys etc, could also be added to the maintenance costs.

- Overhead costs for a shipping company are traditionally also included in the operational costs. They have been neglected in this model, but they're addition would more accurately reflect the companies true operational costs.

Chapter 6

Conclusion

With the polar ice caps melting there has been an increasing availability and ease of transit for vessels through the Arctic seaways. Using the Northern Sea Route or the Northwest Passage decreases the distance to be travelled between ports in Europe, Asia and North America. However, a shorter distance does not always mean a shorter transit time and the risks and challenges that Arctic shipping faces are complex and inter-connected. Environmental concerns, shipping markets, ship and crew safety, ship design & construction and available Arctic infrastructure all effect the feasibility of using the Arctic seaways as operational shipping routes.

This thesis outlined the development of a Cost-Benefit Model that includes Polar Code mandated factors such as, POLARIS route planning. The model has the ability to use real-time ice data and economic inputs like additional insurance premiums, canal tolls, port fees, crew wage & training costs, bunker prices, and unexpected maintenance costs. The model also uses ship parameters and ice resistance calculations with POLARIS operational limitations applied to more accurately estimate ship transit time through ice-covered waters. The CBM highlights the complexity involved in answering the question: Are the Arctic seaways a feasible alternate route, and if so what ice class vessel should be transiting through the Arctic? The answer, simply put, is that it depends on: the particular characteristics of the ship of interest, the market conditions, the current bunker prices, the current freight rate, the season and ice conditions when the voyage is undertaken, the policies regarding and availability of icebreakers for escort, the ability to negotiate canal tolls and by how much, and the experience & training of the ships crew and owner with navigation in ice covered waters.

The results of the research simulation run for this project showed that given the right combination of parameters and variables the Arctic seaways can be a feasible alternative to the southern routes. In the low differential case study (representing the summer months) the FS1A ship operating on the northern routes was always the most economical option from all perspectives. If considering only the PC4 ship, it is again most economical to take the northern routes versus the southern ones for this ship in the low differential case study. In the high differential case study (represented the winter months), from a RFR perspective, the PC4 ship is never the most economically feasible ship compared to the FS1A ship. However, the PC4 ship is still able to transit safely independently throughout the winter, while the FS1A ship requires icebreaker support and operational speed limits. Thus, from a time-saved perspective the PC4 ship on the northern routes is still the fastest option compared to both ships on the southern routes and the FS1A ship on the northern routes.

The interpretation of the CBM results depends on the ice data inputs, the accuracy of the voyage, operational and capital inputs as well as the market conditions within which the results will be analyzed. The future of Arctic shipping depends on many global factors, climatic variables, international policies, and continued research. With the adoption of the Polar Code, IMO and the shipping community have taken a step towards making sure that future voyages will be safe and profitable for crew, vessel and environment.

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Appendix A

Ice Data

A.1 Northern Sea Route

Ice data for the NSR from [Riska and Salmela, 1994].

$C_{firstyear}$ First Year Ice Concentration in tenths
$C_{multiyear}$ Multi Year Ice Concentration in tenths
h_i Maximum Level Ice Thickness in m
h_s Average Ridge Sail height in m

Table A1: Ice Data for NSR [Riska and Salmela, 1994]

Pechora Sea												
Area I	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	NA	NA	NA	NA	6	3	1	0	0	0	NA	NA
h_i	0.7	0.9	1.1	1.2	1.2						0.3	0.5
h_s	1	1	1	1	1	1	1				1	1
$C_{multiyear}$	0	0	0	0	0	0	0	0	0	0	0	0
Western Kara Sea												
Area II	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	10	10	10	9	9	8	4	1	0	2	8	10
h_i	0.9	1.1	1.3	1.4	1.5					0.1	0.4	0.6
h_s	1.2	1.2	1.2	1.2	1.2	1.2	1.2				1.2	1.2
$C_{multiyear}$	0	0	0	0	1	2	2	2	1	1	1	0
Eastern Kara Sea												
Area III	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	10	10	10	10	9	7	6	4	3	6	9	10
h_i	1.2	1.4	1.6	1.7	1.8					0.3	0.6	0.9
h_s	1	1	1	1	1	1	1				1	1
$C_{multiyear}$	0	0	0	0	1	1	1	1	1	0	0	0
Laptev Sea												
Area IV	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII

$C_{firstyear}$	10	10	10	10	9	8	6	3	2	7	9	10
h_i	1.3	1.5	1.8	1.9	2					0.2	0.7	1
h_s	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$C_{multiyear}$	0	0	0	0	0	2	0	0	0	0	0	0
Western East Siberian Sea												
Area V	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	10	10	10	10	9	8	6	4	4	8	10	10
h_i	1.5	1.7	1.9	2	2,1					0.4	0.8	1.1
h_s	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$C_{multiyear}$	0	0	0	0	0	1	1	1	0	0	0	0
Eastern East Siberian Sea												
Area VI	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	10	10	10	10	9	9	7	4	5	8	10	10
h_i	1.4	1.6	1.8	2	2					0.4	0.7	1.1
h_s	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
$C_{multiyear}$	1	1	1	0	0	0	0	0	1	2	2	2
Chukchi Sea												
Area VII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
$C_{firstyear}$	10	10	10	9	8	5	3	2	2	3	7	10
h_i	1	1.2	1.4	1.6						0.2	0.5	0.8
h_s	2	2	2	2	2	2	2	2	2	2	2	2
$C_{multiyear}$	2	2	2	2	2	1	1	0	0	1	2	2

A.2 Northwest Passage

Stage of Development		
Ice Category (RIV)	Stage of Development	Ice Thickness
Ice Free	C_t = <1	h_i = 0
New Ice	S = 1 or 2	h_i < 0
Grey Ice	S = 4	h_i = 10-15 cm
Grey White Ice	S = 3 or 5	h_i = 15-30 cm
Thin 1st year, 1st Stage Ice	S = 6 or 8	h_i = 30-50 cm
Thin 1st year, 2nd Stage Ice	S = 7 or 9	h_i = 30-70 cm
Medium 1st year Ice 2nd Stage	S = 1•	h_i = 20-120 cm
Thick 1st year Ice	S = 4 •	h_i > 120 cm
2nd year Ice	S = 8 •	h_i = ?
Light Multi-year Ice	S = 7 •	h_i = ?
Heavy Multi-year Ice	S = 9 •	h_i = ?

Figure A1: Numeric Stages of Development Representation

All concentrations are in tenths.
C_T = Total Ice Concentration
C_{1stYr} = Concentration of first year ice
C_{Old} = Concentration of old ice (Multi-year ice)
C_{Young} = Concentration of young ice
C_{New} = Concentration of new ice

See Figure A1 for legend to numeric representations of stage of ice development.
S_{1stYr} = Numeric representation of first year ice stage of development, determined with ice concentration
S_{Old} = Numeric representation of multi-year ice stage of development
S_{Young} = Numeric representation of young ice stage of development
S_{New} = Numeric representation of new ice stage of development

Table A2: Ice Data for NWP [Canadian Ice Service, 2016a]

Area	C_T	C_{1stYr}	C_{Old}	C_{Young}	C_{New}	S_{1stYr}	S_{Old}	S_{Young}	S_{New}
January									
Baffin	9	7	1	1	0	9	90	3	1
E Parry	10	9	1	0	0	10	90	3	1
W Parry	10	7	2	0	0	10	90	3	1
Amundsen	10	9	0	1	0	10	90	3	1
A. Mouth	10	9	0	1	0	10	90	3	1
Mackenzie	10	9	1	1	0	10	90	3	1
Beaufort	10	8	2	0	0	10	90	3	1
February									
Baffin	9	8	0	1	0	9	90	3	1
E Parry	10	9	0	1	0	10	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	10	9	0	0	0	10	90	3	1
A. Mouth	10	9	0	0	0	10	90	3	1
Mackenzie	10	8	1	0	0	10	90	3	1
Beaufort	10	8	2	0	0	10	90	3	1
March									
Baffin	10	9	0	0	0	10	90	3	1
E Parry	10	9	0	1	0	10	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	10	10	0	0	0	10	90	3	1
A. Mouth	10	9	0	0	0	10	90	3	1
Mackenzie	10	8	1	0	0	10	90	3	1
Beaufort	10	8	2	0	0	10	90	3	1
April									
Baffin	10	9	1	0	0	10	90	3	1
E Parry	10	9	0	1	0	10	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	10	10	0	0	0	10	90	3	1
A. Mouth	10	10	0	0	0	10	90	3	1
Mackenzie	10	9	1	0	0	10	90	3	1
Beaufort	10	8	2	0	0	10	90	3	1
May									
Baffin	9	8	0	0	0	9	90	3	1
E Parry	9	8	0	1	0	9	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	10	9	0	1	0	10	90	3	1
A. Mouth	9	9	0	1	0	9	90	3	1
Mackenzie	9	8	1	0	0	9	90	3	1
Beaufort	10	7	2	0	0	10	90	3	1

Area	C_T	C_{1stYr}	C_{Old}	C_{Young}	C_{New}	S_{1stYr}	S_{Old}	S_{Young}	S_{New}
June									
Baffin	7	7	0	0	0	7	90	3	1
E Parry	6	5	0	0	0	6	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	8	7	0	0	0	8	90	3	1
A. Mouth	7	7	0	0	0	7	90	3	1
Mackenzie	7	6	1	0	0	7	90	3	1
Beaufort	9	7	2	0	0	9	90	3	1
July									
Baffin	4	4	0	0	0	4	90	3	1
E Parry	4	4	0	0	0	4	90	3	1
W Parry	10	8	2	0	0	10	90	3	1
Amundsen	6	6	0	0	0	6	90	3	1
A. Mouth	3	3	0	0	0	4	90	3	1
Mackenzie	4	3	1	0	0	4	90	3	1
Beaufort	8	6	1	0	0	8	90	3	1
August									
Baffin	1	0	0	0	0	4	90	3	1
E Parry	1	1	0	0	0	4	90	3	1
W Parry	7	5	2	0	0	7	90	3	1
Amundsen	0	0	0	0	0	4	90	3	1
A. Mouth	0	0	0	0	0	4	90	3	1
Mackenzie	2	1	1	0	0	4	90	3	1
Beaufort	3	2	1	0	0	4	90	3	1
September									
Baffin	0	0	0	0	0	4	90	3	1
E Parry	0	0	0	0	0	4	90	3	1
W Parry	4	2	2	0	0	4	90	3	1
Amundsen	0	0	0	0	0	4	90	3	1
A. Mouth	0	0	0	0	0	4	90	3	1
Mackenzie	1	0	1	0	0	4	90	3	1
Beaufort	1	0	1	0	0	4	90	3	1
October									
Baffin	0	0	0	0	0	4	90	3	1
E Parry	2	0	0	0	1	4	90	3	1
W Parry	7	1	2	2	2	7	90	3	1
Amundsen	0	0	0	0	0	4	90	3	1
A. Mouth	0	0	0	0	0	4	90	3	1
Mackenzie	1	0	0	0	0	4	90	3	1
Beaufort	0	0	0	0	0	4	90	3	1

Area	C_T	C_{1stYr}	C_{Old}	C_{Young}	C_{New}	S_{1stYr}	S_{Old}	S_{Young}	S_{New}
November									
Baffin	4	0	0	2	1	4	90	3	1
E Parry	10	3	1	5	1	10	90	3	1
W Parry	10	4	3	3	0	10	90	3	1
Amundsen	8	0	0	5	3	8	90	3	1
A. Mouth	8	0	0	5	3	8	90	3	1
Mackenzie	9	1	0	6	2	9	90	3	1
Beaufort	8	1	1	4	2	8	90	3	1
December									
Baffin	8	4	0	3	0	8	90	3	1
E Parry	10	8	1	1	0	10	90	3	1
W Parry	10	7	3	0	0	10	90	3	1
Amundsen	10	7	0	3	0	10	90	3	1
A. Mouth	10	7	0	3	0	10	90	3	1
Mackenzie	10	7	0	2	0	10	90	3	1
Beaufort	10	7	1	2	0	10	90	3	1